CONCEPTUAL OIL DISPERSION MODELING, LOWER COOK INLET-SHELIKOF STRAIT

by

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PREFACE

This report describes a study of conceptual oil dispersion modeling for Lower Cook Inlet and Shelikof Strait, Alaska. The work was performed under Contract No. NA80RACOO075 between Dames & Moore and the National Oceanic and Atmospheric Administration. In addition to the study reported herein, other studies performed under Contract No. NA80RACOO075 include an oil spill trajectory analysis for Lower Cook Inlet and Shelikof Strait, a wind transition matrix analysis, and an evaluation of CODAR data taken in Lower Cook Inlet. These studies have been previously submitted under separate cover to OCSEAP.

This study was supported by the Bureau of Land Management through interagency agreement with the National Oceanic and Atmospheric Administration, under which a multi-year program responding to needs of petroleum development of the Alaskan continental shelf is managed by the Outer Continental Shelf Environmental Assessment Program (OCSEAP) Office.

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1. INTRODUCTION

1.1 PURPOSE

This study was initiated by the Outer Continental Shelf Environmental Assessment Program (OCSEAP) on behalf of the Bureau of Land Management. This is one of a series of studies conducted by Dames & Moore to investigate the behavior Of hypothetical oil spills on the Alaskan Outer Continental Shelf. The previous studies have been limited to simulation of centroidal trajectories within Lowe r Cook Inlet and Shelikof Strait. There were two primary reasons for limiting these studies to the use of trajectory models: 1) to respond to BLM's immediate needs for oil spill risk assessment data in conjunction with their environmental impact statements; 2) to employ those strategies and algorithms that were consistent with the data base available on environmental forcing fields in the study area.

While continued trajectory studies will no doubt be required in the future, it is now appropriate to begin those studies and develop those tools that will meet BLM's long range needs to reliably describe and forecast the fate of spilled oil on the Alaskan Outer Continental Shelf. The continued environmental studies in the Gulf of Alaska provide increased confidence in our knowledge of the driving forces which now appear to justify more sophisticated modeling approaches.

To this end, the present study focused on reviewing, evaluating, and recommending existing numerical techniques and algorithms used to predict the fate of spilled oil in the marine environment. Consideration of state-of-the-art techniques for modeling the dispersion, weathering and transport of an oil slick has resulted in the development of a conceptual oil spill model. This model blends the most attractive features of applied technology with the specific physical and chemical characteristics of Lower Cook Inlet and Shelikof Strait, Alaska.

1.2 SCOPE

This study was conducted in accordance with the scope of services for Task II detailed in the Dames & Moore proposal, "Oil Dispersion Analysis, Lower Cook Inlet and Shelikof Strait, Alaska," RFX41-436-2905, for National Oceanic and Atmospheric Administration, July 19, 1979, "Proposal Addendum~ Oil Spill Dispersion Analysis," RFx41-436-2905, August 22, 1979, and "Proposal Addendum, Oil Spill Dispersion Analysis," RFx41-436-2905, October 14, 1979, subsequently amended in a letter dated February 4, 1980.

1.3 OBJECTIVES

The primary elements of the scope of services for Task II presented in the above documents are "summarized below:

1. Evaluation of Eulerian and Lagrangian spreading algorithms.
2. Establish techniques to be used to model the selected weathering phenomena.
3. Evaluation of wind field models applicable to Lower Cook Inlet and Shelikof Strait.
4. Investigate the need for depth averaged or layered hydrodynamic models for Lower Cook Inlet and Shelikof Strait.

1.4 BACKGROUND

This study does not attempt to report on or provide complete review and documentation of available models and methods that have been applied to oil spill simulations. The interested reader will find thorough and comprehensive treatments of the subject matter in Stolzenbach et al. (1977), Oceanographic Institute of Washington (1977), Mackay and Patterson (1978), Wheeler (1978), and Spaulding (1978). What is attempted herein is to present state-of-the-art techniques for applied oil spill dispersion simulations that can be adopted for application to Lower Cook Inlet and Shelikof Strait, Alaska.

Given the state-of-the-art of forecasting oil spill movement, the most reasonable approach is still to assume that the overall problem can be decoupled into a series of quasi-independent parts. This treatment generally results in the following separation of environmental and physiochemical features:

- Wind Fields
- Current Fields
- Dispersion and Weathering

Due to the strong coupling between these aspects, it is difficult to separate wind, wave, and tidal effects from the total circulation pattern to extract net currents. However, solving the problem globally using a circulation model that incorporates a wind field model, tidal hydrodynamics, and water mass characteristics to predict the advection of a slick may not be any more reliable than existing approaches and would undoubtedly require significant increases in monetary and time resources.

A standard approach is to create a variety of wind fields corresponding to different meteorological conditions over the study area either using a model or through subjective or objective interpretation of synoptic wind field data. 'The current fields for a variety of oceanic and tidal conditions are likewise created using either a model or through subjective or objective interpretation of available data. These results generally provide the basic input data to any oil spill model. The accuracy and confidence that can be assigned to these fields should play a major role in determining the degree of sophistication to apply in dispersion and weathering aspects of an oil spill model.

The first two influences, wind and current, are primary environmental input requirements to oil spill trajectory studies. In the trajectory approach basic assumptions and empirical relationships are utilized in modeling the centroidal behavior of an oil slick. Trajectory studies are quite useful in providing probability and risk assessment information for preliminary planning and alternative evaluation of offshore oil and gas development. However, to adequately assess the environmental consequences of offshore oil and gas exploration, the spatial and physicochemical properties of a potential oil spill also need to be addressed. This leads to the third influence listed above; dispersion and weathering. One primary objective of the Task II effort concerning oil dispersion modeling was to evaluate, describe, and recommend existing spreading and weathering algorithms that would be implemented during our 1981 fiscal year studies.

The following sections of this report discuss wind field, hydrodynamic and oil dispersion modeling, respectively. The final section presents the approach to integrating the recommended numerical techniques and algorithms and how they would be applied to model the dispersion and transport of spilled oil in Lower Cook Inlet and Shelikof Strait, Alaska.

2. WIND FIELD MODELING

2.1 OBJECTIVES

It is important to accurately characterize the wind drift component in an oil spill model because it is usually a strong function of time and space and tends to dominate surface mass transport. Errors in the specifications of the wind field may significantly alter a spill trajectory. The specification of a realistic wind field over a nearshore, mesoscale region is not an easy task because of complexities introduced by the land-sea interface and inland terrain features.

This section describes the predominant flow regimes in the region of interest, presents a wind field model which is suitable for reproducing those flow regimes, and describes the methodology for actually applying the model to the region. The reasons for choosing the model and its strengths and weaknesses are also outlined.

2.2 WIND FIELD MODEL CONSIDERATIONS

2.2.1 Flow in Lower Cook Inlet

Flow patterns in Lower Cook Inlet and Shelikof Strait are primarily determined by the surrounding terrain (Reynolds et al., 1979). Drainage winds are also important in the vicinity of coastlines, but tend to be localized, extending only on the order of twenty kilometers offshore.

There are four predominant wind directions in the area: from the north-northeast (down Lower Cook Inlet), from the south-southeast (up Shelikof Strait), from the west (through Iliamna Gap), and from the east-southeast (from the Gulf of Alaska) (see Figure 2-1). The northerly flows predominate in the winter, while the southerly flows occur more frequently in the summer (Brewer et al., 1977).

Also present during most of the year is an elevated inversion layer, with the underlying surface layer generally 500 to 1500 m in depth. Measurements of the temperature and winds aloft in the Lower Cook Inlet and Shelikof Strait area have indicated that the surface layer may frequently be thought of as well-mixed vertically (Reynolds, 1980). This surface layer is deepest during the summer since the air has become vertically well-mixed as a result of its extended contact with the warm ocean. During the winter, the surface layer is much shallower because the cold, dry air from the interior of Alaska has only had brief contact with the ocean.

2.2.2 Mesoscale Wind Field Models

In order to construct a surface flow field for this region which would reproduce the complex, orographically and thermally produced flows, ideally one ought to employ a full three-dimensional mesoscale model. Examples of such a model can be found in Mahrer and Pielke (1976, 1977), Nickerson (1979), and McNider et al. (1980). However, the major shortcomings of a high resolution, multi-level model are its substantial cost as well as its input data requirements. A model with smaller computational requirements which duplicates the main results of the complicated model is an attractive compromise.

A model which avoids the need for considering the vertical dimension by following vertically uniform columns of air below the inversion would seem to be very appropriate for the Lower Cook Inlet and Shelikof Strait region. The model of this type which has received the most extensive discussion, analysis, and application was designed by Lavoie (1972).

Lavoie (1972) found that there exists a well-mixed atmospheric layer capped by an inversion during lake-effect storms over the Great Lakes. Thus, a three-layer structure is generated when cold continental air masses undergo surface heating due to their passage over the warm lake water. Daytime oceanic trade winds can be described as having a well-mixed layer below 2 km in which the potential temperature and wind fields are homogeneous in the vertical and the layer is capped by an inversion. Lavoie (1974) modeled the three-layer thermal structure which occurs when the trade winds flow over a heated island. The three-layer thermal structure assumed by Lavoie has been observed experimentally and applied analytically by various investigators. Burke (1945) made use of the structure in his explanation of the transformation of polar continental air to polar maritime air by a warm ocean. Asai (1965) also considered this structure in his study of cold air outbreaks over the Sea of Japan.

Lavoie's model has also been extended by others to analysis of the sea breeze flow (Goodin, 1976), forecasting of regional air flow and pressure patterns (Keyser and Anthes, 1977), analysis of terrain influences on flow (Overland et al, 1979) and air quality impact modeling (Drake et al., 1971; Kern, 1974; Keyser and Anthes, 1976).

Barrientos and Hess (1980) at NOAA's Techniques Development Laboratory (TDL), are currently developing **an oil spill** trajectory model which includes a boundary layer flow model. Only preliminary results are presently available, but this model will be examined upon its completion for possible adaptation to Lower Cook Inlet.

2.3 LAVOIE LAKE-STORM MODEL

2.3.1 Description of the Model

Lavoie (1972) developed a three-layer, mesoscale model to be used in the analysis of lake-effect storms over the eastern half of Lake Erie and its drainage basin. This model included the surface influences of friction, heating and topography, but did not include any moisture variables. The three layers in the model are a constant flux layer at the surface (I), a well-mixed, homogeneous layer (II), and a deep, stable upper layer (III) (see Figure 2-2). The dry thermal structure at the initial time is shown in Figure 2-3, where θ represents the potential temperature (temperature that a parcel of air would have if brought adiabatically from its initial state to the standard pressure of 1000 rob.) and where Z is the altitude above some datum plane (usually mean sea level). Layer I is characterized by a superadiabatic lapse rate (potential temperature decreases with height) in which there is an upward transfer of heat and a downward transfer of momentum; usually this layer is arbitrarily assumed to be 50 m thick. In Layer II, the lapse rate is dry adiabatic since the layer is assumed to be well-mixed by strong winds and surface heating. Finally, Layer III is a deep stratum possessing a constant, stable lapse rate. It is possible, without violating the derivation of the governing equations, to modify Layer I if Layers II and III retain their basic character. That is, Layer I could be either neutral or stable and its depth could be any specified quantity. Hence, the applicability of the model can be broader than originally intended if one is sufficiently cautious.

In the Lavoie mesoscale model the pressure field is determined by the density distribution alone without reference to the motion fields; hence, the pressure field is always in hydrostatic balance (see Ogura, 1963). Estoque (1963) justified the hydrostatic approximation in a sea breeze model through an order of magnitude argument for the vertical component of the momentum equation. Hovermale (1965) justified the hydrostatic balance for gravity waves induced by corrugated terrain if the square of the vertical wavelength is much less than the square of the horizontal wavelength. Hovermale's analysis is applicable to Lavoie's model and his criterion is satisfied because the characteristic wave-length in the horizontal is tens of kilometers while the characteristic wavelength in the vertical is five kilometers or less.

The initial set of equations for the Lavoie model consists of the horizontal equations of motion for the wind field (u, v), the hydrostatic pressure equation, the thermodynamic energy equation for the potential temperature, the equation of state for dry air, and the conservation of mass equation. These equations are only applied in Layer II. Since Layer II is homogeneous in the vertical, the above equations are integrated vertically from the top of the surface friction layer to the top of the well-mixed layer. The altitude of the top of Layer II is denoted by h. Hence, the final equations consist of **a** set which govern the behavior of the well-mixed layer as a whole; the dependent variables are the wind field (u, v), potential temperature, and the altitude h. The average vertical velocity in Layer II is given by the continuity equation. These variables are functions of the horizontal coordinates (x, y) and time t. For a given set of boundary and initial conditions, this system is analogous to the shallow-water equations of oceanography.

The influence of Layer I is represented in the above system by parametrized terms in the momentum and energy equations. That is, the transfer of momentum from Layer II to Layer I and the transfer of heat from Layer I to Layer II are parametezized by the bulk aerodynamic formulation, see

Priestly (1959) and Roll (1965). The influence of Layer III on Layer II is accounted for in the horizontal pressure gradient terms in the momentum equations.

The major assumptions in the above model are as follows:

1. Neglect the effects of curvature of the earth;
2. Neglect the small contributions to the Coriolis force due to vertical motions;
3. Neglect the vertical advection terms in the various conservation equations;
4. Assume the pressure distribution is hydrostatic;
5. Assume the three-layer thermal structure (with possible modifications in Layer I);
6. Assume the parametrized influences of Layers I and III or Layer II;
7. Assume that the stress at Z = h is negligible compared to the stress at Z = 2s and that the Wind is geostrophic in Layer III; and,
8. Assume the vertical homogeneity of the physical quantities in Layer II.

The basic equations applying to a fluid parcel in the mixed layer are:

$$\frac{D\bar{V}}{Dt} = -K f \bar{V} - \alpha \nabla P + \alpha \frac{\partial \tau}{\partial z} \qquad (1)$$

$$\frac{D\theta}{Dt} = -\frac{\alpha\,\theta}{C_p T}\frac{\partial Q}{\partial z} \qquad (2)$$

$$\frac{1}{\alpha}\frac{D\alpha}{Dt} = \nabla \circ \bar{V} + \frac{\partial w}{\partial z} \qquad (3)$$

$$\frac{\partial P}{\partial z} = -\frac{g}{\alpha} \qquad (4)$$

$$\theta = \frac{\alpha P_*^k}{R P^{k-1}} \qquad (5)$$

where $\bar{V}$ is the horizontal velocity vector
f is the Coriolis parameter
α is the specific volume
P is the atmospheric pressure
τ is the eddy stress vector
θ is the potential temperature
C_p is the specific heat for air
T is the temperature
Q is the vertical heat flux
w is the vertical velocity component
g is the acceleration of gravity
R is the specific gas constant
P_* is the reference pressure
$K = R/C_p$

The equations solved by Lavoie (1972) in the mixed layer are:

$$\frac{D\bar{V}}{Dt} = -Kf\bar{V} \cdot F_i - \left(h_i - h\right) f\bar{\psi} + \frac{g}{\theta_h}\left(\theta - \theta_h - \frac{\Gamma}{4}(h - h_i)\right)\nabla h + \frac{g}{\theta}\left(h - z_s\right)\nabla\theta - \frac{C_d}{\left(h - z_s\right)}|\bar{V}|\,\bar{V} \tag{6}$$

$$\frac{D\theta}{Dt} = \frac{C_h\,|V_s|}{\left(h - z_s\right)}\left(\theta_o - \theta\right) \tag{7}$$

$$\frac{Dh}{Dt} = w_h + \left(\frac{1}{\Gamma}\frac{\partial\theta}{\partial t}\right)_{\theta=\theta_h} \tag{8}$$

where ψ is the shear in the geostrophic wind
h_i is the initial height of the inversion
h is the height of the inversion
θ_h is the potential temperature at the base of the inversion
Γ is the vertical gradient of potential temperature
z_s is the top of the surface layer
C_d is the drag coefficient for momentum
C_h is the drag coefficient for heat
θ_o is the potential temperature at the surface
w_h is the vertical velocity at the top of the mixed layer

The terms in equation (6) represent acceleration due to Coriolis forces, acceleration due to the pressure gradient force, acceleration due to shear in the geostrophic wind, acceleration due to horizontal gradients in the depth of the mixed layer, acceleration due to horizontal gradients in potential temperature, and acceleration due to drag forces.

The term in equation (7) represents time rate of change in potential temperature resulting from convective heating from below.

The terms in equation (8) represent change in the height of the inversion base due to synoptic scale vertical velocity there and a term to maintain the first-order discontinuity in θ at h whenever the inversion disappears.

Lavoie solved these equations iteratively until a steady state solution was reached. This required use of the upstream differencing algorithm for the advection terms.

2.3.2 Applications of the Model

Goodin (1976) used the model to study the sea breeze circulation in Los Angeles. The return flow aloft generally associated with the sea breeze is counterbalanced by large-scale onshore flow aloft in Los Angeles. As a result, the flow in the stable layer is nearly geostrophic. The model calculated the surface temperature as a function of time of day and surface characteristics using an iterative solution to the surface heat balance equation. The onset, strength and duration of the sea breeze near the coastline were predicted well. Gradients in terrain and offshore flows were not considered.

Keyser and Anthes (1977) modified the Lavoie model to accommodate time dependent solutions in order to produce a short term forecast. Energy-conserving parameterizations for the entrainment of heat and momentum from the upper stable layer into the mixed layer and for convective adjustment were also introduced. The model was used with real-time data to produce and verify a six hour forecast for the daytime over the Middle Atlantic States. Spatially varying surface roughness and terrain (Appalachian Mountains) were assumed as well as a sinusoidally varying sensible (turbulent) heat flux. Comparison of computed and measured surface pressure and temperature patterns indicated a generally realistic simulation.

Overland et al. (1979) modified the Lavoie equations by placing the advective terms into flux form to maintain conservation of scalar quantities. A staggered grid was also used to avoid the numerical propagation of gravity waves. Terrain was allowed to protrude above the mixed layer thus allowing relatively steep terrain to be included. The model was applied to Puget Sound basin in Washington state. The model was able to reproduce the measured surface wind vectors on the days simulated and seemed well suited for regions with orographically forced flow regimes.

Drake et al (1971) used the Lavoie model to study the air quality of the Four Corners area of the southwest. The study met with limited success generally because of the rugged terrain in the area (the mixed layer was required to follow the terrain). Lavoie's model was used almost unchanged.

Kern (1974) also used the model to analyze an air pollutant transport problem. Tritium data from the Savannah River Laboratory were used in the study. A simple Gaussian plume model and trajectory model with interpolated wind fields were used in addition to the Lavoie model to compute the transport of the tritium. The results obtained using Lavoie’s model were substantially better than all except the retrospective calculation which used the actual wind data.

Keyser and Anthes (1976) used a version of the Lavoie model similar to that described in Keyser and Anthes (1977) to study the sensitivity of the model to variations in certain important parameters. The model results were most sensitive to vertical shear in the geostrophic wind. Less sensitivity to the height of the top of the model and stability of the upper layer was found. Limited studies were made using a passive contaminant.

2.3.3 Strengths and Weaknesses

Some of the advantages and limitations of the Lavoie model (and its subsequent versions) have been discussed in the previous sections. However, they will be summarized here.

It is most important to note that the Lavoie model is a good compromise between computational cost and physical realism. The vertical dimension has been removed which substantially simplifies the problem. However, the major physical phenomena which affect the flow are still included--topography, surface heating and roughness. As a result, the input data requirements are reduced substantially.

As described in Section 2.2.1, the Lower Cook Inlet and Shelikof Strait area seems to meet the requirement that the atmosphere is well-mixed below the inversion layer (Reynolds, 1980). Areas with atmospheric conditions which significantly depart from this structure are not appropriate for modeling with the Lavoie approach.

Since Layer III is passive, sea breeze phenomena which produce a significant return flow aloft cannot be accurately simulated. The land-sea breeze is not a significant feature of the overall flow in Lower Cook Inlet (Reynolds, 1979).

Entrainment of mass from Layer III into Layer II was not permitted in the original Lavoie formulation. Keyser and

Anthes (1976, 1977) and Overland et al. (1979) have modified their versions to include this phenomenon.

The upstream differencing scheme which was used by Lavoie (1972, 1974) is highly damping and as such is suitable only for steady state solutions. The centered difference scheme used by Keyser and Anthes is more appropriate for time dependent solutions.

The most important limitation of the model in the Lower Cook Inlet region may be the specification of the inflow boundary conditions, since errors at the upwind boundary can propagate into the interior rapidly. The edges of the grid boundary will have to be placed far enough from the region of interest in order to avoid terrain interferences near the boundary which could introduce anomalous gravity waves into the calculation.

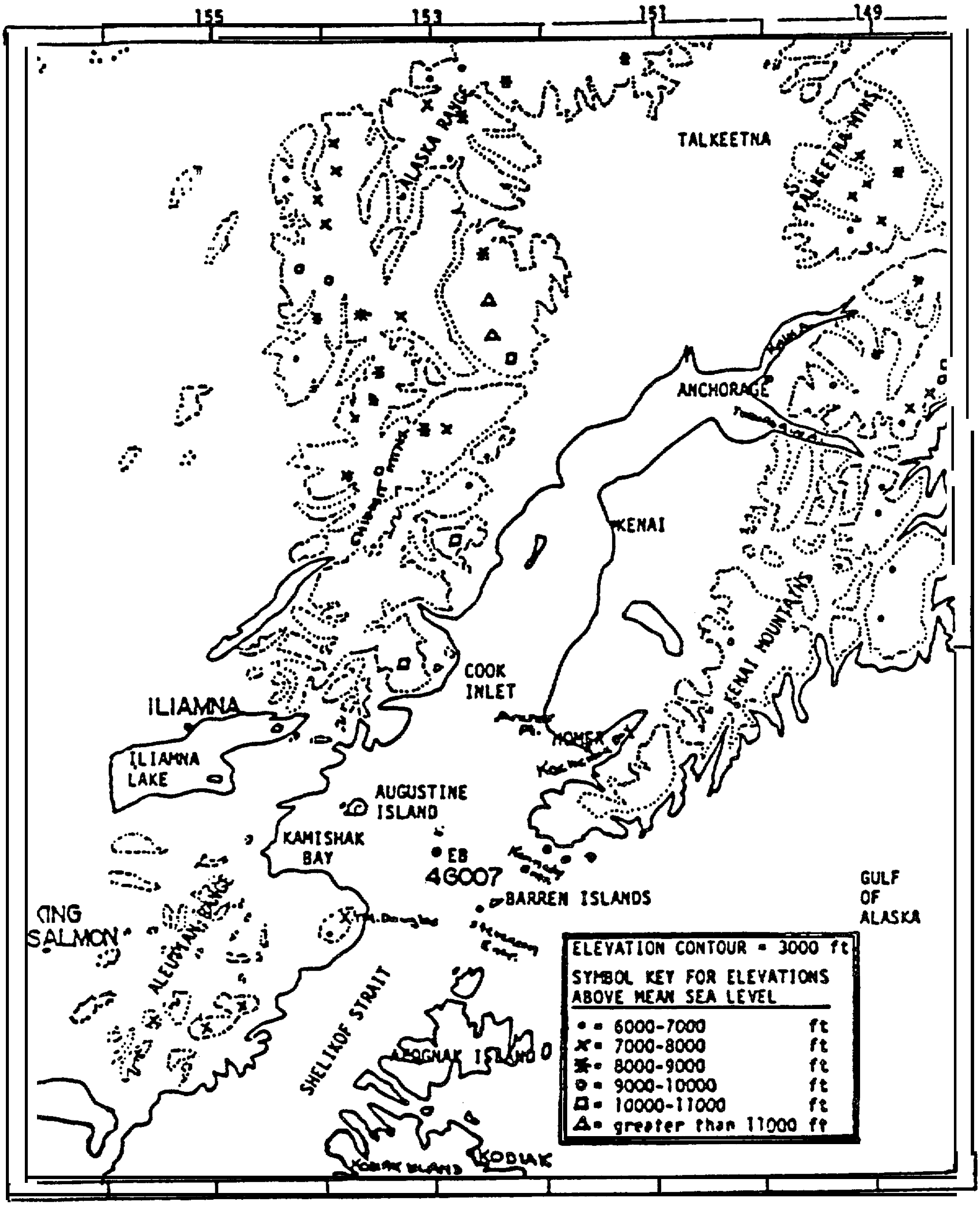


FIGURE 2-1: TOPOGRAPHIC MAP OF COOK INLET.

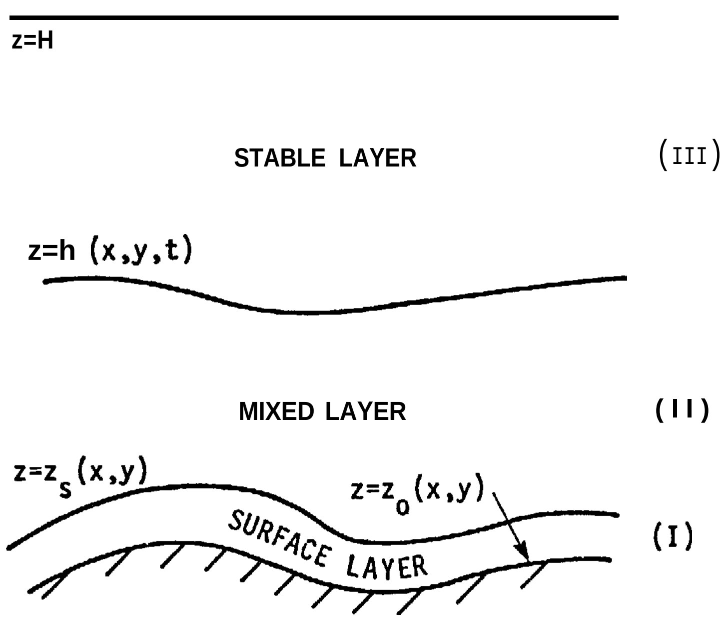


FIGURE 2-2: LAVOIE MODEL LAYER DEFINITION.

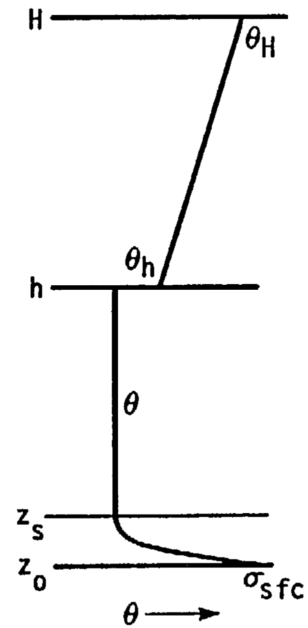


FIGURE 2-3: LAVOIE MODEL THERMAL STRUCTURE.

3* HYDRODYNAMIC MODELING

3.1 INTRODUCTION

The influence of currents on an oil spill is of major importance in determining the ultimate fate and behavior of a spill. It will be assumed that the wind and current effects may be completely decoupled (Wang, 1974; Ahlstrom, 1975; Munday et al., 1970; Miller et al., 1975), as this leads to considerable ease in the handling of the equations. There is limited evidence (Schwartzberg, 1971; Reisbig, 1973) that the two effects are non-linearily coupled.

A variety of methods have been used to specify the surface current behavior and its influence on an oil spill. The recommendation to use a hydrodynamic model for generating surface currents in the study area is based on: 1) a desire to evolve the oil dispersion model capabilities closer to a real time forecast; 2) to increase the accuracy in modeling the magnitude and variability of surface currents in spatial and time dimensions. This latter point has been a major source of subjectivity in past oil spill trajectory studies in Lower Cook Inlet and Shelikof Strait. Currents would be calculated in an objective fashion making use of physically measured data to provide calibration and verification.

3.2 CURRENTS IN LOWER COOK INLET AND SHELIKOF STRAIT

The currents in the study region are dominated by tidal and geostrophic effects with intermittent pulses presumably due to atmospheric forcing (Muench, 1980). Cook Inlet has a large tidal range, up to 25 feet in the upper reaches (Mungall and Matthews, 1973), due to the combined effects of tidal resonance and flow constriction. By contrast, there is a tidal node situated between Kodiak Island and the mainland caused by the tide advancing through both the Kenai and

Shelikof Straits (Pearson, 1980). A coastal jet, specifically the Kenai current (Schumacher, 1980), flows into the study region from a southeasterly direction through the trench between the Kenai Mountains and Kodiak Island. It has a significant effect on the flow patterns in Lower Cook Inlet (Muench, 1980). Residual currents in this region, apparent when tidal effects are subtracted from current records, may be partly attributed to directional fluctuations in the Kenai current.

In addition to tidal and geostrophic effects, freshwater flows into Cook Inlet such as river discharges should be considered. River discharges generate currents directly, while melt-water and precipitation runoff lead to salinity and temperature gradients where mixing occurs with salt water. These gradients cause density variation and hence induce baroclinic currents. Temperature gradients are also induced by differential solar heating due to depth variations. Royer (1979) concluded that precipitation and runoff are important to coastal dynamics in the Gulf of Alaska region. However, as yet, insufficient quantitative data is available to assess the relative importance of these factors. The same difficulty is meet when attempting to determine the influence and importance of current stratification.

3.3 PREVIOUS STUDIES

A wide range of analytical techniques have been applied to determine ocean currents ranging from use of published tide and mean current tables to three-dimensional numerical models. Stochastic models, which are commonly used in predicting turbulence dominated motion, are not suitable in this case.

A number of investigations have been conducted involving modeling the coastal waters of Alaska. Mungall and Matthews (1973) developed a two-dimensional alternating-direction explicit finite difference model to study the tidal dominated

Upper Cook Inlet. The model's salient feature, the use of unequal grid spacings, allowed a greater resolution to be achieved in a region of special concern. This approach to current modeling is essentially the classical method in which a solution to an approximated form of the Navier-Stokes equations is sought. The equations result from mass continuity and momentum considerations. Mungall and Matthews made the assumptions of a two-dimensional depth averaged velocity field and ignored the convective acceleration and inertia terms.

An alternative to the classical approach is the diagnostic model of Gait and Pease (1977). The dynamic method of calculating geostrophic currents is an example of diagnostic modeling. The model was developed on the assumption that the required field input of salinity and temperature were easier to determine than tide and current data required in a model such as Mungall and Matthews. A combination of geostrophic and Ekman dynamics is used in conjunction with the fluid density data to determine the baroclinic and surface Ekman flows. The spatial resolution of the model is limited to the spacing of the input data. The model also shows the marked effect of bathymetry on flow which is particularly important in Cook Inlet. The tidal currents would need to be superimposed.

Leendertse and Liu (1978) developed a three-dimensional turbulent energy model for circulation studies in the Bering Sea. A three-dimensional model is required where variation of longitudinal velocity with depth substantially affects surface flows. In addition, knowledge of vertical velocities is necessary in regions where vertical circulations induce surface effects. Leendertse and Liu used a layered technique as an approximation to the full three-dimensional Navier-Stokes equations. The vertical dimension is modeled by considering velocities at a number of horizontal layers.

Other numerical oil spill studies involving hydrodynamic models have generally used either available tidal and current data explicitly, Blaikley et al. (1977), Murray et al. (1970), Stewart et al. (1974), or various two-dimensional depth-averaged models, Premack and Brown (1973), Wang (1974), Miller et al. (1975).

3.4 CHOICE OF HYDRODYNAMIC MODEL

The important considerations in selecting the most suitable hydrodynamic model are the dominant aspects of the flow in the region, the accuracy and detail of available field data, and the form in which the output will be used. As coupled tidal and geostrophic currents are present, some form of numerical model is considered necessary. The complex bathymetry, density gradients, and possible stratification suggest a full three-dimensional numerical effort be undertaken. However, other considerations prevail. Field data required to calibrate and validate such a model is not available and a major effort would be required to collect such data. It is not obvious that the vertical effects are significant considering the approximations made elsewhere in the proposed model. The study of Leendertse and Liu showed only small vertical velocities in the neighboring Bering Strait region. The operational cost of a three-dimensional model is up to an order of magnitude greater than an equivalent two-dimensional model. Finally, available three-dimensional models are more research tools than state-of-the-art application models. Consequently, use of a three-dimensional model does not appear to be justifiable at this time.

The model of Gait and Pease attempts to avoid the problems of obtaining accurate current and tide data by using salinity and temperature measurements. However, data are required at a resolution corresponding to the intensity of the output required and would involve a considerable amount of field measurement throughout the region. In addition, tidal currents would have to be calculated and added separately. Problems were encountered due to shelf wave phenomena which, due to the trench and shelf topography of the study region, could also occur if the model were applied to Lower Cook Inlet.

Although current and tidal data is required for a "classical" hydrodynamic model, such as that of Mungall and Matthews, it is only required for use as boundary conditions. Such data is presently available. Therefore, a two-dimensional depth-averaged model capable of handling both tidal and current boundary data appears to be the most suitable form of hydrodynamic model for the study as it is presently conceived.

The form of the output required from the hydrodynamic model is dependent upon time scale considerations involving the complete oil spill model. Repeated applications of currents calculated for, say, an M2 tidal cycle would not include the effects of residual current fluctuations and longer tidal cycles which may prove to have a significant impact on the fate of an oil spill. These time scale considerations would be resolved during validation of the complete oil dispersion model.

3.5 TIDAL2

The hydrodynamic model proposed for use in the study is the Dames & Moore numerical model TIDAL2 (Runchal, 1977). This model is based on the classical shallow water equations (Stoker, 1957) which can be shown to be related to the Navier-Stokes equations. The equations are solved by means of Integrated Finite-Differences (IFD) similar to that used by Leendertse (1970). The salient features of the IFD technique are ease and economy of application and numerical stability.

The numerical scheme is space-staggered, split time level, and semi-implicit. As with the model of Mungall and Matthews, unequal grid spacings may be used to optimize resolution in specific regions of interest.

TIDAL2 has been successfully applied to a number of studies including circulation in Kanahoe Bay, Hawaii (Dames & Moore, 1977), and determining velocities and stage heights in a tidally dominated river in Florida (Dames & Moore, 1979). Boundary data is accepted either as current or tidal measurements and sources equivalent to inflow of rivers or runoff can be incorporated. The model is calibrated to reproduce field measurements by adjustment of empirical bottom friction coefficients.

4. OIL DISPERSION MODELING

4.1 PRCCESSES OF OIL DISPERSION

The processes recommended for inclusion in the oil dispersion model are those that have a major impact on the ultimate fate of a two-dimensional surface oil slick. The recommended algorithms for modeling these processes are only as sophisticated as knowledge of the environmental conditions and process interactions at present will reasonably allow. The processes considered in the recommended oil dispersion model are: a combined balance-of-force and Fickian diffusion approach to spreading, wind and current coupled advection; empirical surface evaporation flux; and vertical dispersion (oil in water emulsification).

Many other physical, chemical, and biological phenomena are involved in the spreading and transport process. Some of the physical processes not included in the model are: source motion, waves, water surface slope, dissolution, direct air-sea interaction (bubble bursting), sinking, sedimentation, tar lump formation, etc. Chemical processes not considered include microbial degradation, uptake by organisms, biological dispersants and supermicrobes.

A full treatment of the relative impact of the above processes on the fate of a surface oil slick is beyond the scope of this study. However, the interested reader can consult such work as Kolpack (1977) , Kuipers (1980), or MacKay and Patterson (1980) for details of proposed modeling techniques, the interactions and complexities, and the relative importance of each process. It should be kept in mind that several processes which have not been included in the model were left out for the simple fact that data necessary to perform the modeling does not and would not exist for the area of concern. Therefore, inclusion of the process using assumed or estimated values was deemed undesirable in that an unknown error would be knowingly introduced. The following sections briefly discuss the processes and algorithms recommended for inclusion in the dispersion model.

4.2 SPREADING

4.2.1 General

Among most applied oil spill studies an important difference exists in the method by which spreading is modeled. Basically, this difference is whether to treat spreading as a dispersion process or by a balance-of-force approach. The following paragraphs discuss the strengths, weaknesses, and applicability of each approach to modeling spreading of oil on water.

4.2.2 Balance-of-Force Approach

Fay (1969) had considered the spreading phenomena as a balance of the forces acting on a slick; gravity, inertia, viscous, surface tension. He concluded that the spreading process on a calm sea could be characterized by three time dependent regimes corresponding to the dominant influence acting on the slick at that time.

The different slick growth regimes and their respective acting physical forces are listed below:

Fay's Spreading Model

Regime	I	II	III
Spreading force	gravitational	gravitational	surface tension
Retarding force	inertial	viscous	viscous

Figure 4-1 shows the spreading regime for a 10,000 ton oil spill. Spreading terminates when the oil slick diameter reaches a maximum size in Regime III. Based on Fay's results the maximum slick radius is predicted to occur when:

$$r = 80.37\ n^{3/8} \tag{9}$$

where r is the radius (in meters) of a circular coherent oil slick and n is the number of barrels of spilled oil. The time (in minutes) required to reach this maximum radius is predicted by:

$$t_s = 52\ (n)^{0.482} \tag{10}$$

Figure 4-2 shows the duration of the different spreading regimes as a function of the volume of oil spilled. The validity of Fay's basic approach has been partially demonstrated by several laboratory studies (i.e., Lee, 1971; Hoult et al., 1970). However, field data from Conomos (1975) showed that Fay's theory applied to non-laboratory conditions greatly underestimates slick growth (Stolzenbach, 1971). Fay's approach considers spreading on a calm, smooth sea, and dispersion by oceanic turbulence is ignored.

4.2.3 Dispersion Approach

The basic concept behind the dispersion approach in modeling spreading is that the physical spreading processes related to oil properties (density differences and surface tension) are subordinate to the effects of shear on the slick boundary produced by random motions in the water.

Murray (1972) presented an approach in which he assumed that spreading can be represented by a Fickian type diffusion process in which the actual forces responsible for spreading the oil are the eddy stresses. The solution or concentration c at any point (x) for any time (t) is given by solving the governing equation

$$\frac{\partial c}{\partial t} = K \frac{\partial^2 c}{\partial \bar{x}^2} \tag{11}$$

where K is the diffusion coefficient.

The solution to equation (11)in one dimension in an infinite medium, for an instantaneous release of mass (m) is the well-known gaussian distribution

$$c = \frac{m}{2\sqrt{\pi K t}} e^{-\left(\frac{x^2}{4Kt}\right)} \tag{12}$$

Kennedy and Wermund (1972) noted that a real oil slick had the same shape as predicted by Murray's theory.

Figure 4-3 shows a comparison between an observed slick outline and slick outlines predicted by Fickian diffusion theory and surface tension theory. It can be seen that spreading of oil is reasonably well defined using the "diffusion" approach dependent on horizontal eddy diffusivity K (Murray, 1972).

Most investigators have chosen to use one approach or the other for modeling spreading of an oil spill. However, both spreading and dispersion processes may be important in determining the overall growth of a slick particularly for time scales measured in a few days. It has been estimated that existing techniques provide at best only an order of magnitude prediction of what an actual oil slick will attain in size (Stolzenbach et al., 1977) .

Figure 4-4 shows a comparison of predictions of slick size using Fay's spreading approach and an oceanic dispersion approach. While both methods seem to underestimate slick size for time longer than a day, the dispersion method give results closer to the field data than Fay's approach.

4.2.4 Combined Balance-of-Force and Dispersion Approach

Another approach to model spreading is to consider the balance-of-force and dispersion separately and then combine them to obtain a total rate of growth. In this context, the use of the term spreading is defined to be the growth of a slick due to a balance-of-force approach. This approach can be represented in mathematical terms as follows:

$$\left[\frac{dR}{dt}\right]_{\text{total}} = \left[\frac{dR}{dt}\right]_{\text{spreading}} + \left[\frac{dR}{dt}\right]_{\text{dispersion}} \tag{13}$$

where $\frac{dR}{dt}$ is the rate of radial growth of the slick

R is the radius of the slick

t is the time.

Stolzenbach (1977) expressed the rate of growth due to spreading by considering a balance of the spreading forces: gravity, surface tension, viscous, and dynamic pressure. The rate of growth due to dispersion was modeled using the results of Okubo (1967) on oceanic dispersion (eddy diffusivity proportioned to the 4/3 power of the cloud size).

Alhstrom (1975) developed one of the earlier models that simulated spreading by a combination of dispersion and balance-of-force processes. Spreading was simulated in this model by the random motion of oil patches using a statistical treatment of turbulent diffusion. The position of the patches at any time have the same gaussian distribution as the concentration of oil would have by solving the diffusion equation. Dispersion was therefore treated as a homogeneous Markov random process. The dispersion coefficient was assumed to be a constant, the sum of a turbulent eddy dispersion coefficient D_E and an "equivalent" dispersion coefficient D_ϕ.

The equivalent dispersion coefficient, D_ϕ is calculated using Fay's relationship for final slick size and time "t_S" to reach it. Thus, D_ϕ is representative of the balance-of-force approach and is only a function of the initial slick volume. For $t > t_S$, D_ϕ is taken as zero.

This approach is attractive because it accounts for both spreading and dispersion processes. However, several weaknesses are apparent. First, assuming a Brownian-like random motion dictates that the diffusivity coefficients D_ϕ and D_E, are functions of neither time or space. Secondly, the direct summation of D_ϕ and DE to obtain an apparent diffusivity constant cannot be supported by any physical reasoning. Also, questions remain as to whether the different phases of the spreading of oil can be treated as "random" processes. For example, the gravity phase is likely to be more "deterministic" than "stochastic".

These weaknesses can be ameliorated to a degree by considering random diffusivity, but using a variable diffusivity coefficient. This coefficient would be variable in time, at least for the oceanic dispersion phase, and in space. This treatment would allow simulation of some anisotropic effects such as slick elongation.

Even though the methodology discussed above cannot be entirely supported on a theoretical basis, it is believed that this approach could provide the best estimate of the governing spreading processes.

As a first estimate for D_E, the oceanic dispersion coefficient as is given by Okubo (1962) is recommended (see Figure 4-5):

$$D_E = 0.0027\,(t)^{1.34} \qquad (14)$$

where:

D_E is the oceanic dispersion coefficient (cm^2/see)

t is time (see).

D_{Φ}, the spreading **diffusivity** coefficient, if assumed constant with time, has been computed by Sahota (1978) using **Fay's** results as:

$$D_{\Phi} = 2300(n)\ `{*}^{2}6^{8}\ (\text{cm}^2/\text{see}) \qquad (15)$$

where:

D_{Φ} is the **diffusivity** coefficient (cm^2/see)

n is the number of barrels of spilled oil.

The total spreading/dispersion coefficient, K_r, for the case of an isotropic spread, would be given by the direct **sum** of the above coefficients as:

for $t < t_s$; where $t_s = 3120\,(n)^{0.482}$

$$K_r = 2300(n)^{0.268} + 0.0027\,(t)^{1.34} \qquad (16)$$

for $t \geq t_s$

$$K_r = 0.0027\,(t)^{1.34} \qquad (17)$$

where:

n is the number of barrels of spilled oil

t is the time in sec

K_r is diffusion **coefficeint** in **cm^2/sec.**

4.2.5 Directional Dispersion

Most dispersive **models Presume a circular slick,** but reports have shown **slick** elongation in the direction of the wind (see Figure 4-6). The reason for this **is** not yet clear (**Kuipers,** 1960). However, it may result from the non-uniform velocity profile in the oil layer (Figure 4-7) which has been shown to increase dispersion in the direction of advection (longitudinal dispersion) (Taylor, 1953). Dispersion of an oil slick in open water should then be modeled as a combination of spreading, lateral dispersion (eddy), and longitudinal dispersion (differential advection).

Garven (1978) suggested the use of anisotropic dispersion coefficients to simulate an elliptical slick. Elongation of the slick was considered to be a function of time. Analysis of field data provided an empirical formula given by:

$$P = -0.175 \log_{10} t + 1.168 \qquad (18)$$

where p = ratio of the minor to major axis of a slick
t = time (in seconds).

It can be seen that p decreases with time, but reaches a constant value of approximately 0.15 in a week or so.

For a dispersive cloud, the standard deviation of a particle position is related to the dispersion coefficient by:

$$\sigma_r = \sqrt{4\ K\ t} \qquad (19)$$

(the diameter of the cloud d is often taken as 6 σ).

Rather than describing the diameter of a slick using a single size parameter, $\sigma_r{}^2$ (radial variance of particle position), an elliptical spill may be characterized by two such parameters σ_x , σ_y (where x and y are respectively the major and minor axes of the slick).

The elongation, p, may now be defined as:

$$\rho = \frac{\sigma_x}{\sigma_y} \qquad (20)$$

and σ_x and σ_y may be related to the radial variance by:

$$\sigma_r^2 = 2\,\sigma_x\,\sigma_y \tag{21}$$

Combining the relationships from equations (20) and (21), an implicit relationship, for σ_x and σ_y can be derived and is given as:

$$\sigma_x = \left(\sigma_x^2 / 2\rho \right)^{1/2} \tag{22}$$

$$\sigma_y = \rho\,\sigma_x \tag{23}$$

From the above equations, it can be seen that the anisotropic dispersion coefficients can be expressed as a function of the equivalent isotropic coefficient K_r and the elongation parameter as given below:

$$K_x = K_r/2\rho \tag{24}$$

$$K_y = pK_x = K_r/2 \tag{25}$$

The random portion of the slick movement can be obtained by combining a random motion in the direction of the deterministic transport obtained using a dispersion coefficient K_x, and a random motion in the perpendicular direction using a dispersion coefficient K_y.

4.3 ADVECTION

4.3.1 General

Advection of oil floating on water is a result of the combined effects of wind, currents, and waves. Investigators have generally considered only wind and current effects on the transport of oil and either disregard the influence of waves or, in fact, implicitly include it in their surface wind drift relationship. Controversy on the comparative influence of these different effects still exist, but most studies generally agree that the final or resultant surface drift magnitude is in the range of 3.0 to 3.5 percent of the local wind speed.

4.3.2 Speed

Shemdin (1972) suggested on the basis of his laboratory data that the surface drift was essentially a wind induced shear current. On the other hand, Bye (1967) and Kenyon (1970) concluded from their analyses of oceanic wave data that the surface drift was primarily a wave induced mass transport.

Wu (1975) presents a comparison of the variation of wind induced surface drift and wave induced surface drift as a function of the fetch length (see Figure 4-8). The sum of the two is the total surface drift and can be seen to be approximately independent of the wind fetch length with a magnitude on the order of 3.5 percent of the wind velocity for long fetches.

Additional uncertainty in predicting wind induced surface drift occurs when net or tidal currents are present. Schwartzberg (1970) and Plate et al. (1970) studied the combined effect of current and wind drift. They concluded that the total surface drift cannot be determined by the simple superposition of current and wind induced drifts.

Tsahalis (1979) reached the same conclusion that the surface drift due to the combined action of currents, winds, and waves cannot be determined by the superposition of the separate drift components. Using a flume and wind tunnel for the experimental design and assuming a scaling law relating model to prototype conditions, empirical formula were obtained relating the surface drift current to a function of 10 meter wind speed and current speed, for co-current and counter-current conditions. These relationships were expressed in terms of non-dimensional groups, $(T-C)/C$ and U_{10}/C, where T is the total drift, C is the current speed, and U_{10} is the wind speed at 10 meters above the water. Table 4-1 presents the resulting empirical relationships for a variety of wind and current conditions. Figure 4-9 presents the experimental results and the empirical fit to the data.

Tsahalis' approach applies only when wind, current, and wave directions are colinear. Deflection effects were not studied in his work. Nevertheless, as a first approximation Tsahalis' approach can be used for the component of the current parallel to the wind. The component of the current perpendicular to the wind can be assumed to contribute a component surface drift of the same direction and magnitude.

4.3.3 Deflection

The deviation or deflection angle that the wind imparts to the surface drift is still a controversial subject. Observations of oil spill trajectories, either real (Smith, 1968) or simulated (Teeson et al., 1980), have consistently shown the deflection angle to be on the order of 10° or less.

Madsen (1977), using a simple assumption of a linear increase in vertical eddy viscosity, arrived at a relationship predicting the surface drift magnitude and direction as function of wind velocity. Inspection of his results show that assuming a surface drift of 3 percent of the wind speed and a deflection angle, $\theta = 10°$, provides a reasonable approximation over a wide range of conditions. This approach was based only on wind induced surface currents and the effects of currents or waves were not included in the investigation.

Kondo et al. (1979) arrived at slightly different results which showed the surface drift magnitude approximately 25 percent larger than given by Madsen and the deflection angle at around 170. As with Madsen's, Kondo's theoretical work is not directly applicable for predicting oil slick movement in a complex sea. Only the component of the surface drift due to the wind was analyzed and the effects of waves and net and tidal currents were ignored.

Field observations show in most cases a very small deflection of the surface drift to the right of the wind direction. The magnitude of this deflection is on the order of a few degrees which is negligible considering the uncertainty in the prediction of the local wind direction (Stolzenbach et al., 1977).

At present a deflection angle of 0° seems appropriate to adopt considering the available field and theoretical results and in view of the uncertainty of the overlying driving wind field itself. Coriolis force acting on an oil slick is orders of magnitude smaller than the shear forces acting on an oil slick and can be neglected.

4.4 WEATHERING

4.4.1 General

Weathering is a time dependent process which changes physical and chemical properties of spilled oil due to exposure to natural elements. Weathering is a general term that covers a variety of complex processes which are strongly interrelated and therefore, should not be considered independently. However, due to the great complexity of this phenomena there have been few attempts to model the complete weathering process based on field or theoretical research. To date, the most generally accepted approach is to separately quantify the most important weathering factors.

Evaporation is nearly always the single most important weathering process during the first few days of an oil spill. However, the importance of natural dispersion has been clearly demonstrated both in experimental spills and in recent, larger spills (Bravo blowout, Ixtoc I blowout, and the Amoco Cadiz oil spill) (Audunson, 1980). Dispersion of oil into the water column below the surface can be important during any stage of the life of an oil slick. Other weathering phenomena such as sinking can become important in later stages of an oil spill and cannot be neglected if the history of the spill is needed for time periods greater than a week or so. Weathering processes such as biodegradation and photo-oxidation are unlikely to be an important factor in removing significant quantities of oil (Berridge et al., 1968), particularly in early stages of an oil slicks exposure.

The primary loss of oil from an oil slick, based on available literature and field experience is due to evaporation to the atmosphere and dispersion into the water column. The uncertainty in modeling evaporation and dispersion processes with state-of-the-art procedures is large enough that attempts to model losses due to other weathering processes will not improve the overall accuracy of the result.

4.4.2 Evaporation

Hydrocarbon evaporation rates are affected by composition, surface area, and physical properties of oil; wind velocity; air and sea temperatures; sea state; and intensity of solar radiation (Wheeler, 1978).

According to Sivadier and Mikolaj (1973), rough sea conditions can triple the early rate of evaporation over calm sea conditions for similar wind speeds.

A number of investigators have developed empirical formulas to calculate the evaporation rate of hydrocarbons from a mixed hydrocarbon substrate. However, no standard formulation has yet been adopted and most models use their own coefficients based on experimental results. Some measure of agreement has been reached in that the resultant coefficients used in the various models are quite close to one another (Yang and Wang, 1977).

Recent studies of Yang and Wang (1977), Sahota et al. (1978), and Audunson et al. (1980) use the same analogy to the molecular diffusion process to express the evaporative flux D of one component in the slick:

$$D = K P / R T_s \tag{26}$$

where:

K is the evaporative mass transfer coefficient
P is the hydrocarbon vapor pressure
R is the gas constant
Ts is the absolute temperature of the oil slick.

A standard formulation of the coefficient K which accounts for significant environmental factors has not yet been accepted. Sahota (1978) used a value of K which was obtained from experiments done by Mackay and Matsugu (1973):

$$K = a U^b \tag{27}$$

where:

U is the wind speed
a and b are experimental constants.

Yang (1977) proposed a different relationship:

$$K = a A^b e^{cU} \tag{28}$$

where:

A is slick area

U is wind speed

a, b, and c are experimental constants.

Audunson (1980) suggested a relation of the form:

$$K = (a + bU)/\delta \qquad (29)$$

where:

U is wind speed

δ is oil thickness

a and b are experimental constants.

The above relationships are very similar and differences are negligible in view of other phenomena influencing evaporation which are not accounted for in these models. These phenomena include sea state (white capping), weather (rainfall, hail storm, solar intensity), inhomogeneity in slick composition, etc.

It is believed that unless a spill is extremely large, , the influence of slick area on evaporative flux will be negligible. As a first approximation and in agreement with state-of-the-art evaporation modeling, given the uncertainties that currently exist, it is sufficiently accurate to relate the coefficient K only to wind speed.

For these reasons, the methodology developed by Mackay and Leinonen (1977) and used by Sahota et al. (1978) to compute evaporative losses is recommended for use in the conceptual model. This method has been recently calibrated (Mackay and Patterson, 1980) using Canadian crude oil.

The evaporative flux E_F is given by:

$$E_F = K_e \, C_i \, p_i \, / \, RT \ (\mathrm{mol.cm^{-2}\ sec^{-1}}) \qquad (30)$$

where:

K_e = evaporative mass transfer coefficient ($cm.sec^{-1}$)

Ci = concentration of ith component in the oil (mole fraction)

Pi = pure component vapor pressure at the oil temperature

R = universal gas constant

T = air temperature above the oil slick.

A relationship giving the evaporative mass transfer coefficient, K_e, has been obtained from experiments by Mackay and Matsugu (1973):

$$K_e = 0.005\ U^{0.78} \tag{31}$$

where U is the wind speed in cm/sec.

This simplified approach to evaporation modeling requires knowledge of the chemical composition of the spilled oil. For computational purposes, the oil is divided into its principal components, volatiles and nonvolatile, and after computing the evaporative losses, the quantity of oil evaporated is removed from the slick.

Associated with the evaporation model is monitoring an oil slick's density which will enable prediction of a slick's tendency to sink, as evaporation removes lighter fractions.

4.4.3 Dispersion (oil in water emulsification)

Natural dispersion (vertical) is the forcing of oil particles from the surface into the water column due to turbulence such as caused by wave action. Dispersion in the water column, as emulsification, depends on oil composition and sea state (Wheeler, 1978).

There have been few field studies in which subsurface concentrations of oil have been measured. Freegarde et al. (1971) and Forrester (1971) reported very small concentrations of hydrocarbons below a slick. In these cases, dispersion accounted for only a few percent of the total oil mass (Stolezbach et al., 1977). On the other hand, results of experiments done at Warren Spring Laboratory on North Sea and Kuwait crude oil indicated that approximately 30 percent of the original mass of an oil slick could be lost in the first 24 hours in a medium sea state (Blaikley et al., 1977). The apparent discrepancy between the results of these studies lies in the fact that dispersion depends strongly on the intensity of turbulence.

Raj and Griffiths (1979) studied the probability density distribution of oil droplets subjected to ocean turbulence by looking at the equilibrium of turbulent pressure against buoyancy and surface tension forces. The results of this work, indicate that a 3.0 meter minimum sea state, defined by significant wave height will tend to initiate globular vertical dispersion of oil. This suggests that dispersion can be negligible in calm seas or of major importance during bad weather.

Several approaches have been used to model or quantify the rate of oil dispersion into the water column as a function of sea state and time. Blaikley et al. (1977) gives estimates of loss-rate ranges for initial spill conditions and also after three and five days at sea (see Table 4-2). The decrease of loss rate with time attempts to account for the effects of increased oil viscosity due to weathering and also the formation of “chocolate mousse”. This approach has been used in the oil spill computer model "Sliktrack" developed at Shell International Petroleum Maatschappij (Blaikley et al., 1977).

Audunson et al. (1980), in the "SlikForcast" model derived from "Sliktrack", used a range for the dispersion constant for the first 10 days dependent on a given sea state. A value of zero percent was conservatively assumed for the dispersion constant after 10 days (see Table 4-3).

The values used in the "SlikForcast" model were estimated from the following empirical formula:

$$a = \alpha_o \left(\frac{\omega}{\omega_o}\right)^2 \tag{32}$$

where:

α, α_o are the natural dispersion rates (day^{-1}) for wind speeds ω, ω_o (m/s) respectively. (For Ekofisk crude oil the value of α_o is estimated to be in, the range of 0.10 to 0.15 day^{-1} for ω_o = 8.5 m/s.)

Sahota et al. (1978) used the results of Holmes (1977) and Blaikley et al. (1977) which assumed values of 15, 25, 35, and 45 percent natural dispersion loss per day corresponding to low (2), medium (4), high (7), and very high (7+) Beaufort Sea state respectively.

Considering the lack of accuracy in the methodology and estimates used to model dispersion, it is recommended that the Audunson formula as given by equation (32) be implemented assuming a maximum value of a = 0.6 day^{-1}. It should be noted that α_o , depending on the specific oil characteristic, is only known to a 50 percent accuracy and, therefore, a cannot be expected to be estimated within an accuracy of, say, 100 percent.

TABLE 4-1
DRIFT COEFFICIENT EXPRESSIONS

The drift coefficient ($\frac{T-c}{c}$) is given as a function of $\frac{U_{10}}{c}$ by the equations identified below based on the range of the value of $\frac{U_{10}}{c}$, where

T = total drift

c = current velocity

U_{10} = wind speed 10m above the water surface.

Coefficient	RELATIVE CURRENT DIRECTION: Countercurrent (opposite direction of wind)		Cocurrent (in direction of wind)	
if $\frac{U_{10}}{c}$ is in the range of	$(-\infty$ to $-35)$	$(-35$ to $0^-)$	$(0^+$ to $20)$	$(20$ to $+\infty)$
then $\frac{T-c}{c}$ is calculated from equation	1	2	3	1

1) $$\frac{T-c}{c} = 0.033\left(\frac{U_{10}}{c} - 1\right)$$

2) $$\frac{T-c}{c} = -1.88 \times 10^{-2} - 1.53 \times 10^{-3}\left(\frac{U_{10}}{c}\right) - 1.78 \times 10^{-3}\left(\frac{U_{10}}{c}\right)^2 - 2.24 \times 10^{-5}\left(\frac{U_{10}}{c}\right)^3$$

3) $$\frac{T-c}{c} = -1.67 \times 10^{-3} - 4.00 \times 10^{-3}\left(\frac{U_{10}}{c}\right) + 3.30 \times 10^{-3}\left(\frac{U_{10}}{c}\right)^2 - 7.56 \times 10^{-5}\left(\frac{U_{10}}{c}\right)^3$$

TABLE 4-2

NATURAL DISPERSION EFFECTS

SEASTATE	DAYS :	Percent Oil Lost/Day 1-3	4-5	6 Plus
Low		10-30%	5-15%	o-5%
Medium		20-40%	10-20%	o-7%
High		30-50%	20-30%	o-lo%
Very High		40-60%	25-35%	o-lo%

(From Blaikley, et al., 1977)

TABLE 4-3

EXAMPLES OF DISPERSION CONSTANTS
(EKOFISK CRUDE)

WIND FORCE	m/s	0-8	7-13	13-20	>20
Dissipation constant λ' in % per day	First 10 days	1-9	5-23	20-46	40-59

(From Audunson, 1980)

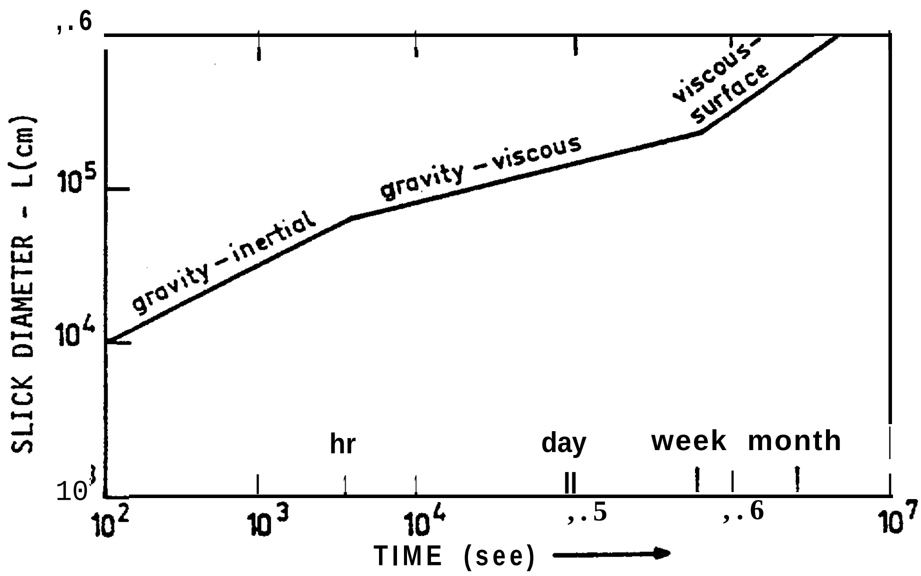


FIGURE 4-l: SLICK SIZE AS A FUNCTION OF TIME FORA 10,000 TON SPILL (FAY, 1969).

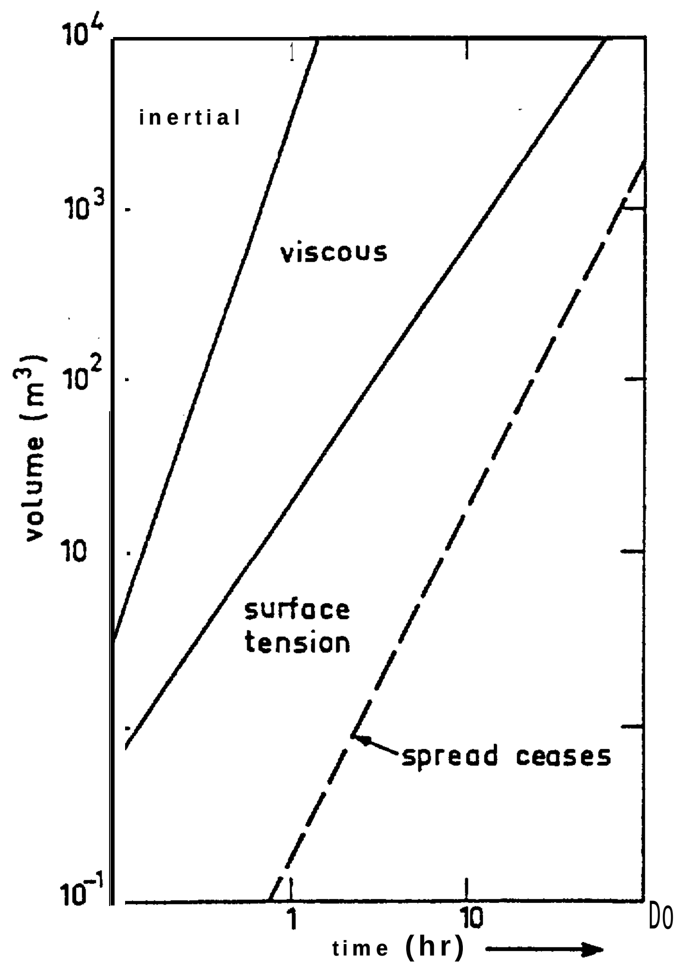


FIGURE 4-2: DURATION OF SPREADING REGIMES (HOULT, 1972).

NOTE : THE CURRENT SPEED, Uest, IS ESTIMATED AT THE AVERAGE VALUE FOR THE INCIDENT (30 CM/S) FOR THE TURBULENCE THEORY, AND ESTIMATED AT 5 CM/S FOR THE SURFACE TENSION THEORY TO MAXIMIZE POSSIBLE AGREEMENTS BETWEEN FAY'S THEORY AND THE OBSERVATION (MURRAy, 1972).

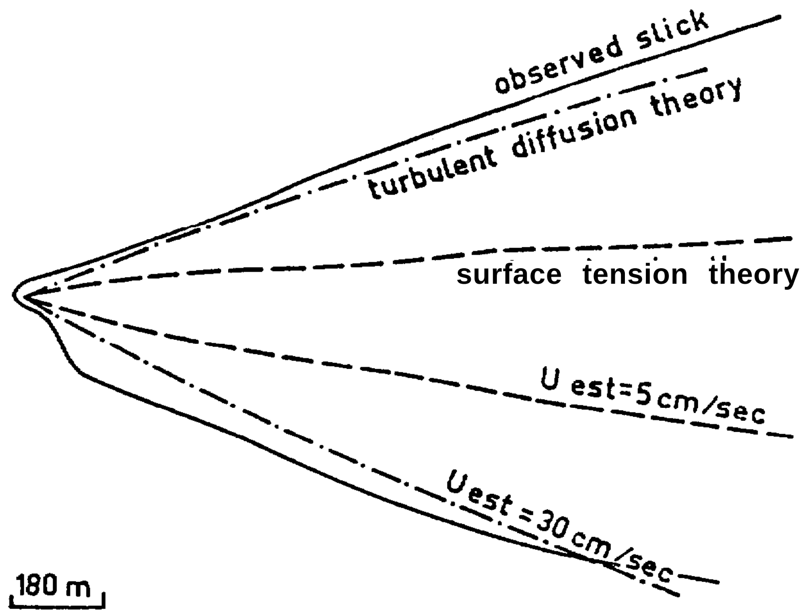


FIGURE 4-3: COMPARISON BETWEEN OBSERVED AND PREDICTED SLICK OUTLINE USING FICKIAN DIFFUSION THEORY AND SURFACE TENSION THEORY OF FAY.

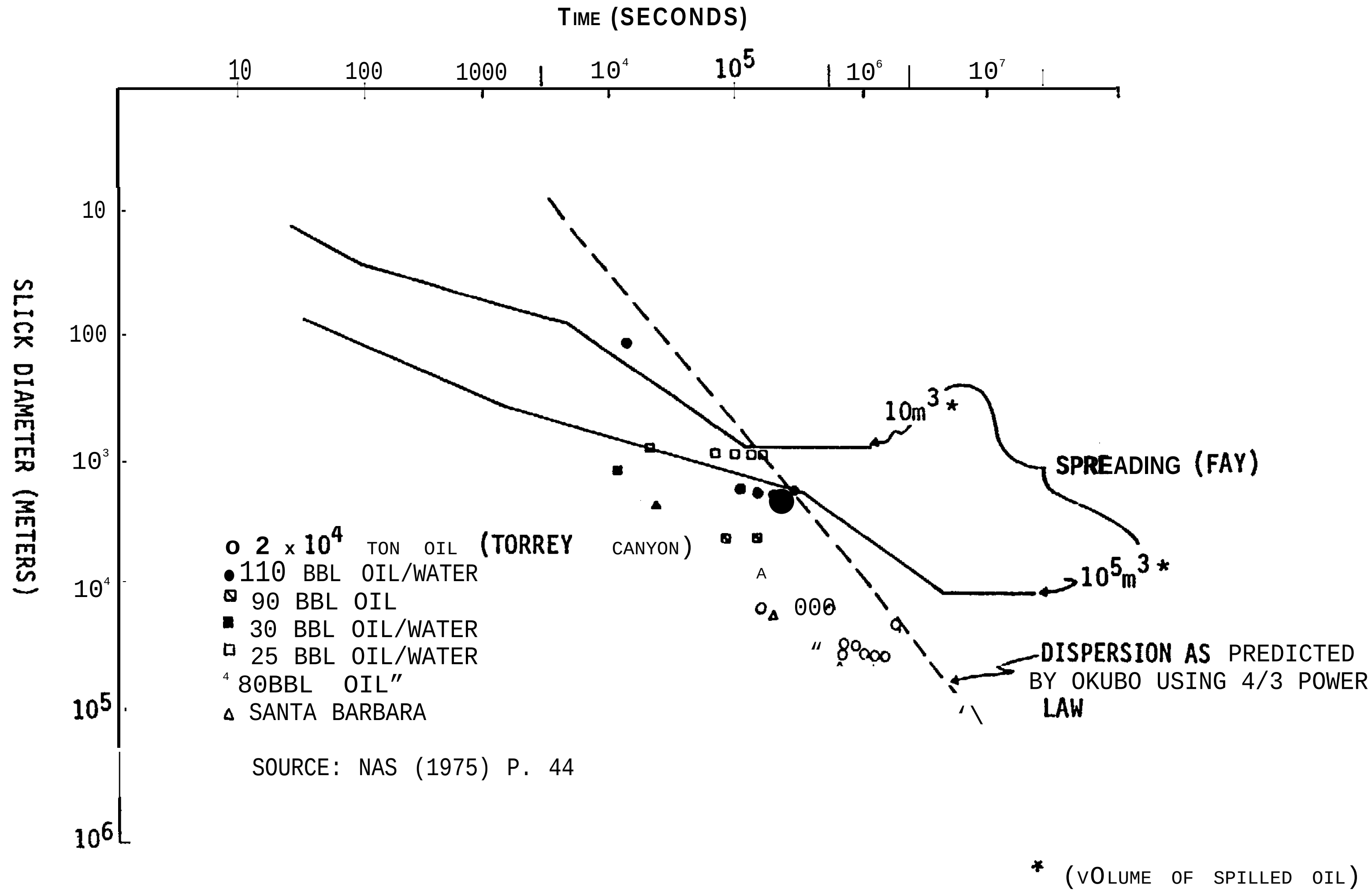


FIGURE 4-4: COMPARISON OF THEORETICAL AND OBSERVED SLICK SIZES

(STOLZENBACH, ET AL, (1977))

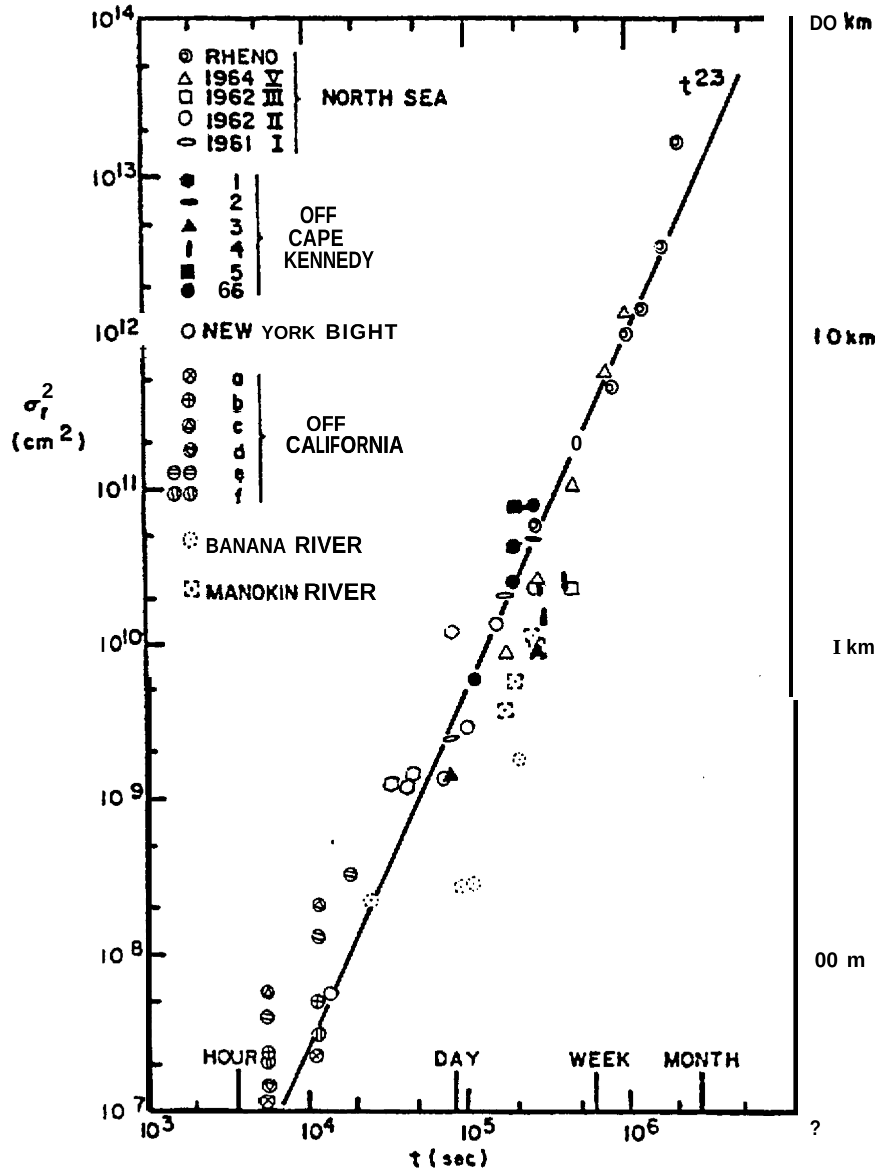
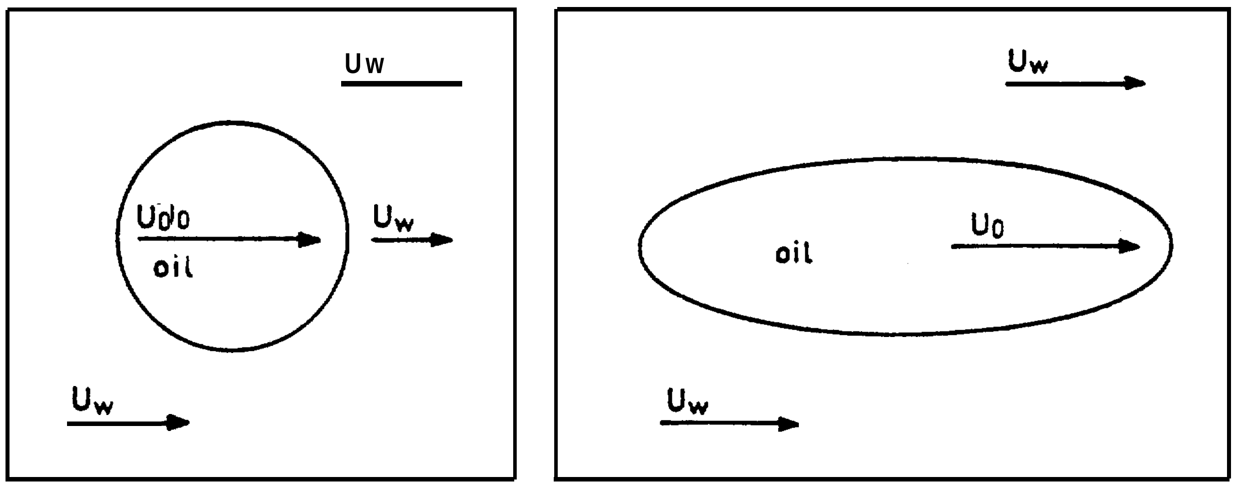


FIGURE 4-5: SURFACE DYE PATCH SIZE, σ-, AS A FUNCTION OF TIME (OKUBO, 1962).



OIL SLICK AT TIME $t=t_0$ OIL SLICKAT TIME $t=t_1>t_0$

u" SURFACE WATER VELOCITY

U* SURFACE OIL VELOCITY

FIGURE 4-6: PLAN VIEW OF OIL SLICK ELONGATION

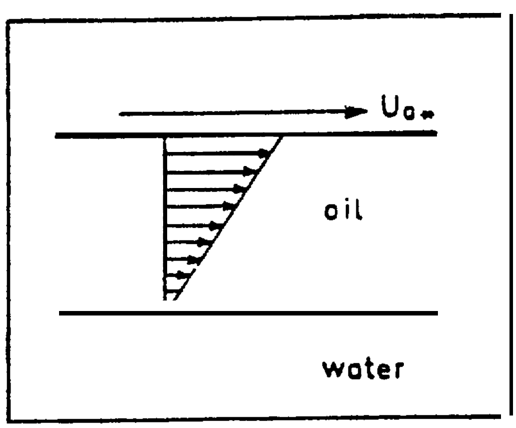


FIGURE 4-7: VERTICAL RELATIVE OIL VELOCITIES

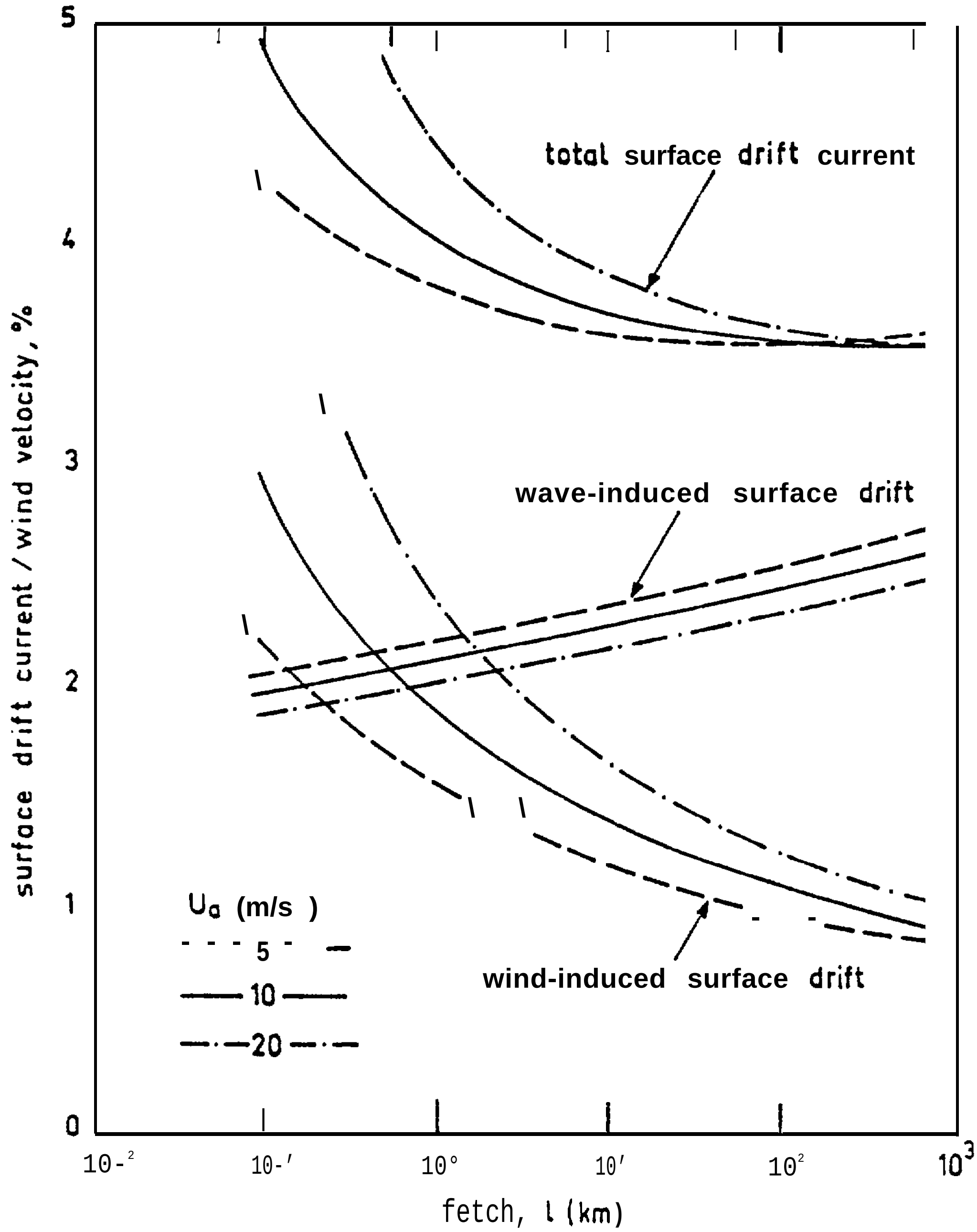


FIGURE 4-8: WIND-INDUCED SURFACE DRIFT CURRENT VARIATION WITH FETCH (WU, 1975).

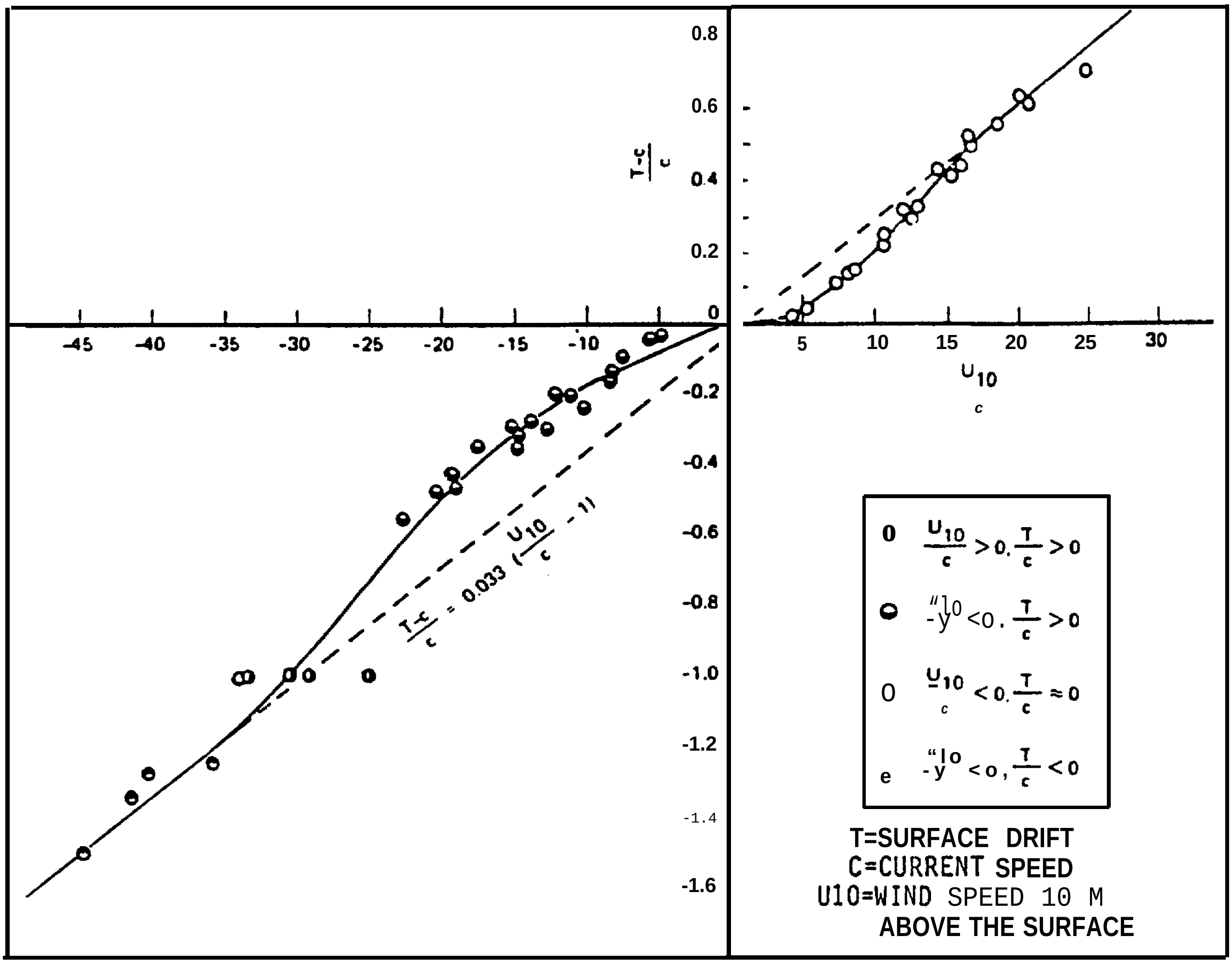


FIGURE 4-9: SURFACE DRIFT RATIO (T-c)/c VERSUS U_{10}/c(FROM TSAHALIS 1974).

5. MODEL INTEGRATION AND APPLICATION

5.1 GENERAL

This section summarizes the oil spill dispersion modeling recommendations for Lower Cook Inlet and Shelikof Strait, Alaska. The integration of the separate components will be presented and their application discussed. It should be reemphasized that the model is in a conceptual state and as such the finer working details are not at present available. This conceptual model embodies state-of-the-art technology tempered with regional characteristics and data accuracy, coverage, and availability considerations which when implemented will result in a significant advancement of oil spill modeling capabilities for OCSEAP and BLM programs.

5.2 WIND FIELD MODEL APPLICATIONS

The typical flow patterns in Lower Cook Inlet and Shelikof Strait were described in Section 2.2.1. It was indicated that a vertically integrated mixed-layer approach could be used for this region. The envisioned methodology for calculation of the wind field will be discussed in more detail in this section.

In order to compute the contribution of the wind drift to an oil slick's movement, the oil spill transport model requires specification of sea surface wind velocity, U_{10}, at each grid point. For specified atmospheric stability and surface roughness conditions, the sea surface wind, U_{10}, can be related to the 50 m wind velocity which will be computed using the Lavoie model. Irwin (1979) has described a power-law approach to this calculation while Businger et al. (1971) have determined the relationship using a similarity solution. The sea surface wind velocity, U_{10}, will be computed following each calculation of the 50 m winds.

The mixed-layer model will use the basic equations originally derived by Lavoie except that improvements incorporated into the code since that time by Keyser and Anthes (1976, 1977), Goodin (1976), and Overland et al. (1979) will be included. The modifications which will be included are improved parameterizations of the entrainment mechanism from the stable layer to the mixed-layer, a more sophisticated surface temperature calculation and improved treatment of flow over and around steep terrain, i.e., terrain will be allowed to protrude above the mixed-layer. The model will then incorporate the best features of the various mixed-layer approaches developed to date.

The mixed-layer model is envisioned to run in a diagnostic (steady-state) mode. Given the required input data (pressure gradient or geostrophic wind) at the 850 mb level, the model would be run to a steady state solution. Steady state solutions of this type resulting from different upper level flows could be generated and stored. These stored wind fields would then be used in sequence for a multiday period. If one selects the upper level wind data corresponding to a particular weather type cataloged by Putnins (1966), then these types could be related to the resulting wind fields. Since Putnins' classification of each day between 1945 and 1963 is known, individual representative days or a specific sequence of days could be selected for computation.

This diagnostic use of the Lavoie model would also be appropriate for eventual use in a near real-time mode if the required upper level pressure gradient or geostrophic wind data could be obtained. Key inputs to this calculation are the forecast values of wind velocity, temperature, and relative humidity available from the National Weather Service. These variables are forecast for 12, 24, 36, and 48 hours in the future using the Limited-area Fine Mesh (LFM) model (Gerrity, 1977) which is run at the National Meteorological

Center in Washington, D.C. The LFM calculations are performed every 12 hours (at OOZ and 12z) using radiosonde data collected throughout North America at those times. The variables are computed on a SO x 50 grid with horizontal spacing of 160 km (see Figure 5-l); the vertical levels are 850 mb (1,500 m), 700 mb (3,000 m), and 500 mb (6,000 m). The computed values are not available until approximately 4 hours after the data collection times as a result of processing delays. The computed variables at 850 mb and possibly 700 mb would be the upper boundary values for the mesoscasle model.

Figures 5-2 through 5-4 show typical, computer-generated pressure surfaces from the LFM model. Figure 5-2 shows an 840 mb pressure surface with some data points indicated, Figure 5-3 shows a 500 mb pressure surface with no data points, and Figure 5-4 shows a close up of Figure 5-3.

5.3 HYDRODYNAMIC MODEL APPLICATION

The hydrodynamic model will be calibrated using existing current measurement data taken in Lower Cook Inlet and Shelikof Strait by PMEL during 1977 and 1978. Estimates of runoff and inflow during the calibration period will be made and included. Tidal forcing will be accounted for by specifying time dependent water surface elevations across two ocean boundaries between Kodiak Island and the Alaskan and Kenai Peninsulas. Currents or flow rates would be specified across these boundaries to simulate the estimated inflow/outflow conditions during the calibration period of record.

Calculated time series of depth-averaged currents would be compared to measured currents at several locations within Lower Cook Inlet and Shelikof Strait. Initial efforts would concentrate on measurements taken in lower Shelikof Strait, due to the relative lack of stratified flow conditions within the Strait and the reasonably- uniform bathymetric profile of the cross section of the Strait. These conditions more closely approximate assumptions inherent in the depth-averaged two-dimensional formulation of the model. If reasonable calibration is obtained for these locations, then efforts can be extended to the increasingly complex bathymetric subsurface and flow regime present in Lower Cook Inlet. If calibration is successful in this region, the model would be run in a verification mode to predict measured currents during a time period different than that used for calibration.

Once calibrated and verified, the model can be utilized in either a near-real time predictive mode or in a deterministic mode. The initial utilization of the model would be for the latter case. A series of characteristic flow conditions could be developed and estimates made for the specified boundary conditions. For example, the following might be chosen as the conditions that would characterize the dominant flow regimes:

- o strong, average, weak inflow at Kennedy and Stevenson Entrances
- o flow reversals through Kennedy and Stevenson Entrances
- o high, average, and low freshwater inflow
- o spring, mean, and neap tidal input boundary conditions

Each separate run would account for a unique combination of these conditions. A simulation period of 24 hours is envisioned with current velocities stored at 1 hour intervals. An interpolation scheme would be utilized to calculate velocities between stored time periods. It may be possible, based on somewhat limited data, to estimate probabilities of occurrence for the separate flow conditions and relate them to seasons as well. If this can be done, the patterns could be cycled daily depending on the season and according to the probability generated in a flow transition matrix. This application would also be consistent with the recommended implementation of the wind field model.

Although variations in residual currents for periods less than 24 hours are not modeled (boundary flows and discharges are assumed constant), the approach would provide more variability than assuming seasonal net current patterns. It would also be possible to add random velocity components, based on statistical analysis of the current meter data, if increased variability of residual currents is desired for periods less than 24 hours. A statistical approach could also be used to interpolate flow magnitude and discharge variations without running the hydrodynamic model for more than the limited base case conditions.

The near real-time application of the hydrodynamic model would require input data describing present runoff and discharge conditions as well as tidal strength and phasing. Estimates could be obtained for freshwater discharge through stage-discharge relationships for gaging stations and synthetic hydrographic analysis for ungaged drainage basins. The tidal strength and phasing could be obtained from NOAA publications and analyses for the current data of interest and, for that matter, for any future date (in a forecast mode). The real problem in running the hydrodynamic model in a near real-time mode is specification of inflow/outflow conditions at ocean boundaries. This may require a statistical treatment, or if a spill occurs, a planned monitoring of currents in the associated straits. Advances in remote acoustical sensing of currents may evolve to the point of providing this information with the rapid response time required.

In addition, use of CODAR generated surface currents could replace or augment the need for a hydrodynamic model in the near real-time operational mode, if the areal coverage is large enough to track a spill over the geographical area of interest.

5.4 OIL DISPERSION MODEL APPLICATION

5.4.1 Spreading

The deterministic approach to a dispersion phenomena typically leads to a second order partial differential equation. Normally, for many practical problems, solutions are obtained numerically with the associated problems of spacial and temporal resolution, numerical instability and artificial numerical diffusion. Application of numerical techniques to the deterministic approach is often mathmetically complex and expensive (Runchal, 1980).

Stochastic techniques on the other hand are conceptually simple and attractive. A spill is divided into n parcels and the dispersion of the parcels is represented simply as a series of random displacements or walks. The direction and length of each displacement are independent random values. For a sufficiently large number of parcels, n, the individual displacements would approximate a normal or Gausian distribution which is representative of a dispersive cloud.

From statistical considerations it can be shown that the random displacement of a given parcel during time t can be given by:

$$\Delta X_s = \left(\int_t^{t+\Delta t} 2 K_x(t)\, dt \right)^{1/2} N_r \tag{33}$$

$$\Delta Y_s = \left(\int_t^{t+\Delta t} 2 K_y(t)\, dt \right)^{1/2} N_r' \tag{34}$$

where:

ΔX_s = displacement in direction of the wind

ΔY_s = displacement perpendicular to the wind

N_r, N_r' = normally distributed random numbers with a mean of zero and standard deviation of unity

K_x, K_y = longitudinal and lateral diffusion coefficients respectively as given by equations (24) and (25).

The numerical integration scheme required to **obtain the displacements can be approximated by using the average value of K_x and KY between the time t and t + Δt:**

$$\Delta X_s = N_r \left(2\, K_x\left(t+\Delta t/2\right)\Delta t\right)^{1/2} \tag{35}$$

$$\Delta Y_s = N_r'\left(2 K_y\left(t+\Delta t/2\right)\Delta t\right)^{112} \tag{36}$$

Though in **principle,** N_r may take any value between $-\infty$ and $+\infty$, in practice, it proves sufficient to limit the magnitude of the extreme values to a low number between 3 and 5.

The longitudinal and lateral diffusion coefficients, K_x and KY, are related to the equivalent isotropic diffusion coefficient, K_r, and the elongation of the slick, ρ, by equations (24) and (25).

The elongation, p , of the slick is given by equation (18) and is a function of time, only reaching an asymptotic value of 0.15 in about a week.

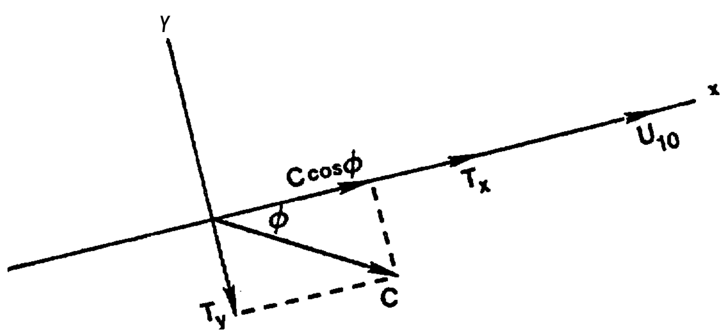
The equivalent isotropic diffusion coefficient, K_r, is defined herein to be the sum of the oceanic turbulent dispersion coefficient, D_E, as given by equation (14) and the pseudo spreading dispersion coefficient, D_ϕ, as given by equation (15). Thus, K_x and KY are both functions of time and spill volume.

At any particular time, the area of the slick is defined to be that area bounded by the envelope of all parcel locations.

5.4.2 Advection

The advection portion of a parcels displacement will be treated in a similar manner to spreading or random motion. That is, advective motion will be decomposed into a component in the direction of the wind and a component perpendicular to the direction of the wind.

The surface drift component in the direction of the wind, T_x, will be obtained from the formulas of Tsahlis presented in Table 4-1. The surface drift component perpendicular to the direction of the wind, T_y, will be assumed to equal the component of current velocity C in that direction. The sea surface wind velocity, U_{10}, is obtained from the wind field model and the current, C, is obtained from the hydrodynamic and tidal currents. These components are defined in the following sketch:



During a time step, At, the resulting displacement is given by:

$$\Delta X_a = \int_t^{t+\Delta t} T_x(t)\,dt \tag{37}$$

$$\Delta Y_a = \int_t^{t+\Delta t} T_y(t)\,dt \tag{38}$$

The numerical integration scheme required to obtain the displacements can be approximated as follows:

$$\Delta X_a = T_x\left(t + \Delta t/2\right)\Delta t \qquad (39)$$

$$\Delta Y_a = T_y\left(t + \Delta t/2\right)\Delta t \qquad (40)$$

5.4.3 Total Displacement

Therefore, based on combined spreading and advection algorithms, total displacement of a particle during a time step, t, is the sum of its displacement due to the advective transport and of its displacement due to random dispersion, and is given as follows:

$$\Delta X_t = \Delta X_s + \Delta X_a \qquad (41)$$

$$\Delta Y_t = \Delta Y_s + \Delta Y_a \qquad (42)$$

Substituting the values from equations (35), (36), (39) and (40) gives:

$$\Delta X_t = N_r\left(2K_x\left(t + \Delta t/2\right)\Delta t\right)^{1/2} + T_x\left(t + \Delta t/2\right)\Delta t \qquad (43)$$

$$\Delta Y_t = N_r'\left(2K_y\left(t + \Delta t/2\right)\Delta t\right)^{1/2} + T_y\left(t + \Delta t/2\right)\Delta t \qquad (44)$$

5.4.4 Evaporation

Application of the evaporation algorithm recommended for this model requires that the oil to be modeled is broken down into n components $(2 \le n \le 15)$ of volatiles and nonvolatile. The physical and chemical properties of each component must be known as a function of their respective mole fraction.

Considering one component of the oil, during a time interval Δt, the evaporative loss of mass, Δm, that is removed from the slick is given by:

$$Am \approx \int_{t}^{t+\Delta t} K_e(t) C_i(t) P_i(t) A(t) M_i \, At / R T \tag{45}$$

This can be approximated if At is small enough (on the order of an hour or so) as:

$$Am = \frac{K_e(t+\Delta t/2) C_i(t) P_i(t+\Delta t/2) A(t+\Delta t/2) M_i \Delta t}{R \; T(t+\Delta t/2)} \tag{46}$$

where:

K_e = evaporative mass transfer coefficient

Ci = mole fraction of the ith component

R = universal gas constant

T = air temperature above the oil slick (°K)

A = area of the oil slick

Mi = molar mass of the ith component

P_i = pure component vapor pressure at the oil temperature.

There are several assumptions which are inherent in treating evaporation in the above manner. The oil slick is modeled as one of uniform thickness which remains perfectly mixed both horizontally and vertically. In actuality, different components spread at different rates and the slick tends to fractionate. Assuming perfect vertical mixing is equivalent to assuming that diffusion within the slick can keep up with evaporation from the slick surface. However, during the beginning of the slick’s life, the slick is at its thickest and evaporation at its fastest. Thus, the proper conditions are presented for diffusion within the slick to be the rate-limiting process. Another approximation is that the oil is a perfect mixture and the behavior and properties of one hydrocarbon are not affected by the presence of others.

In reality, most oil mixtures are not ideal. There is interaction between fractions. For example, there is a heat of solution caused by mixing that must be overcome in addition to the heat of vaporization, for evaporation to occur. At the present state-of-the-art, these complexities in modeling evaporation have not adequately been resolved. Therefore, the evaporative flux from each idealized fraction is linearly confined for each time step.

The total mass that evaporates during one time step, t, is:

$$\Delta m_t = \sum_{i=1}^{n} \Delta m_i \tag{47}$$

This mass is removed from the slick and a new slick density is computed.

5.4.5 Vertical Dispersion

The vertical or natural dispersion model recommended for integration into the oil dispersion model is the approach described by Audunson (1980). The percentage of oil dispersed per day is estimated from α, which is calculated by equation (32). The percentage of oil, Q, dissipated during the time step At would then be given as:

$$Q = \frac{\alpha \quad \Delta t}{1440} = \frac{\alpha_0}{1440}\left(\frac{\omega}{\omega_0}\right)^2 \Delta t \tag{48}$$

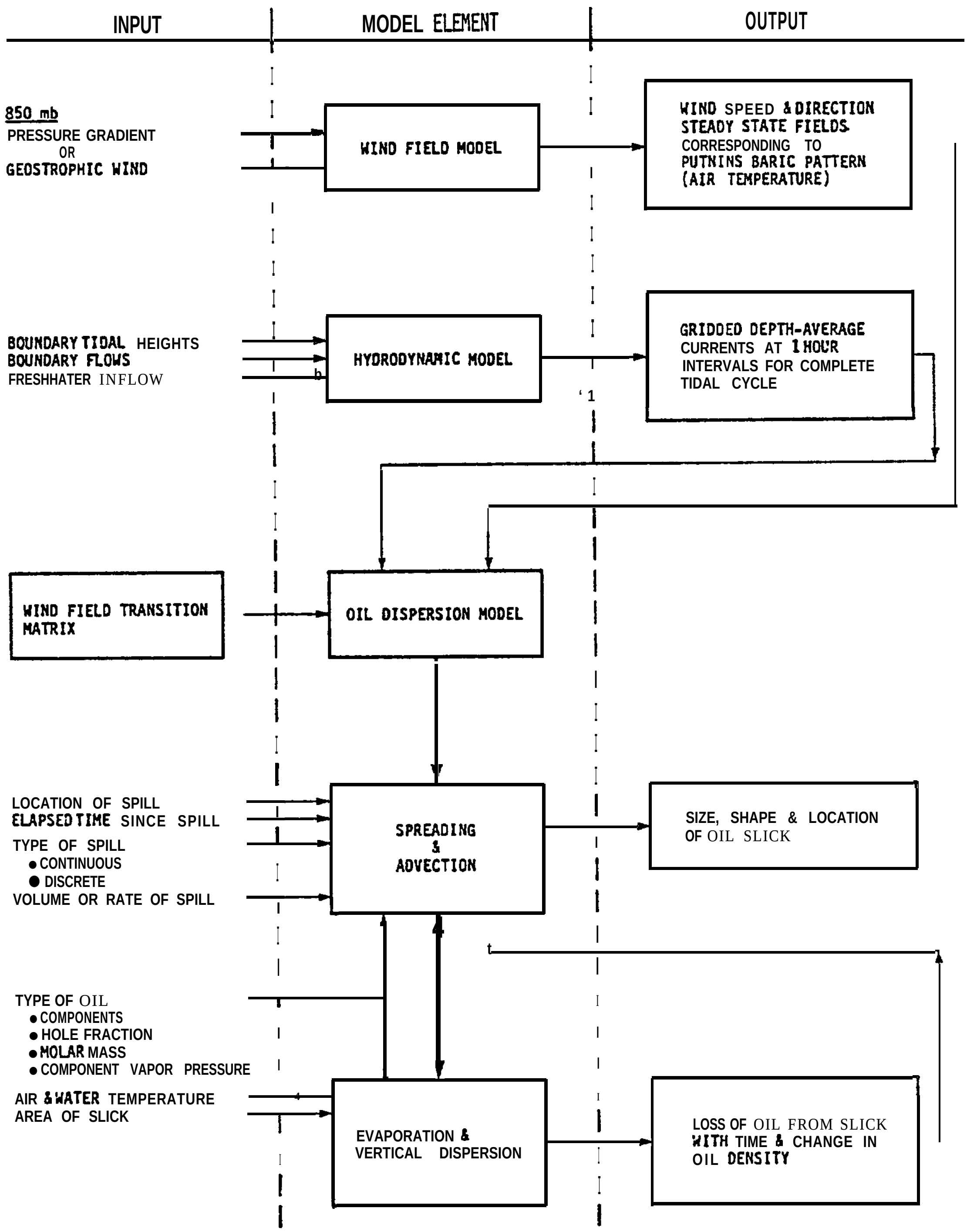
where At is in minutes.

The value of Q is conservatively assumed to go to zero after 10 days of simulation. The value of Q is calculated using the local value of ω, the 10 meter wind speed, obtained from the wind field program.

5.5 MODEL INTEGRATION

A simplified flow chart of the inajor. elements of the conceptual oil dispersion model is presented in Table 5-1. The table indicates the type of input required, the interaction of the model elements, and the output. The model will be able to run in either a deterministic or near real-time mode, although at present the deterministic mode is envisioned to be the approach utilized in the next generation of oil spill studies applied to Lower Cook Inlet and Shelikof Strait.

TABLE 5-1
FLOW CHART
OIL DISPERSION MODEL INTEGRATION



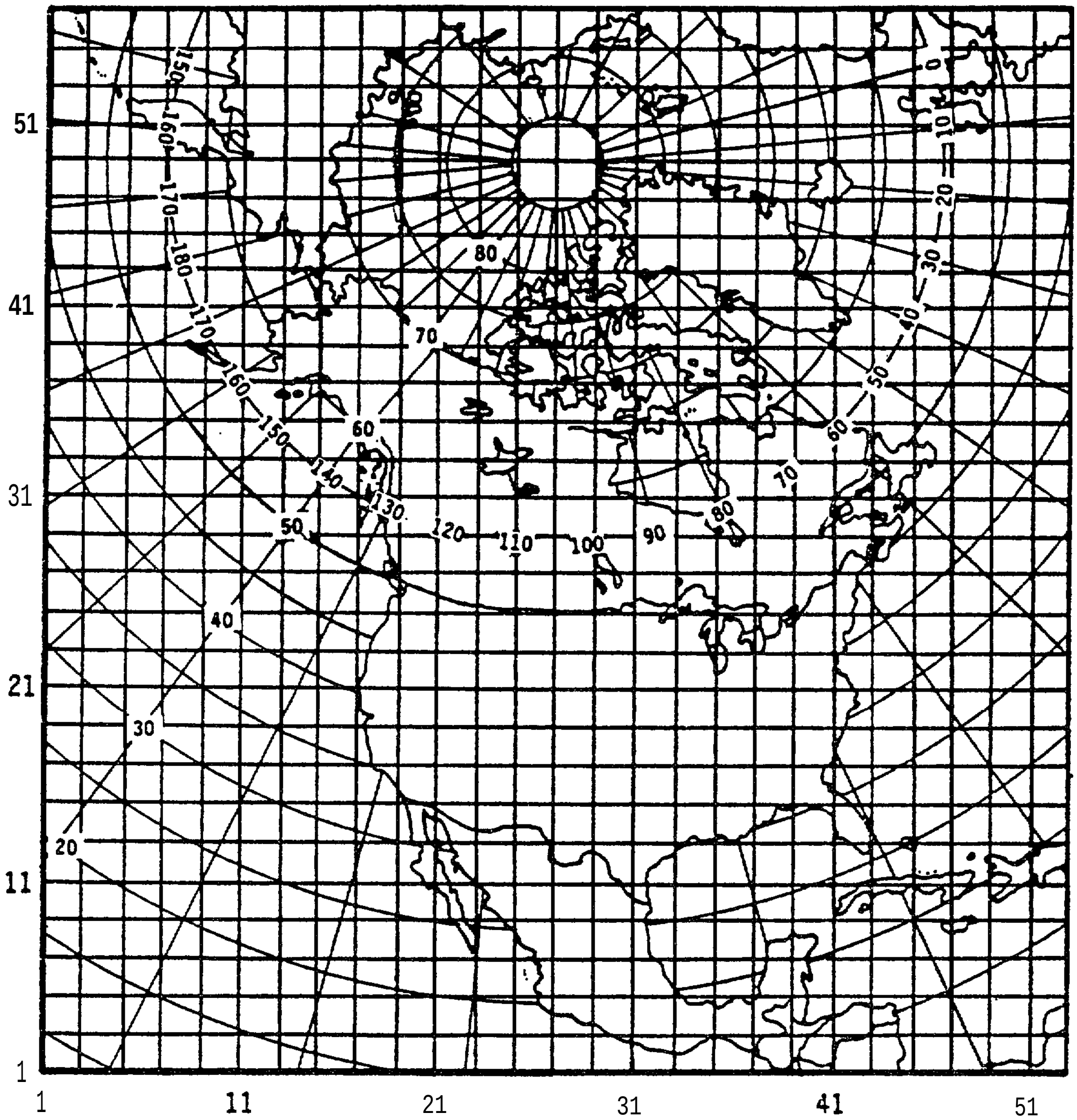


FIGURE 5-1: AN APPROXIMATION OF THE LFM GRID.

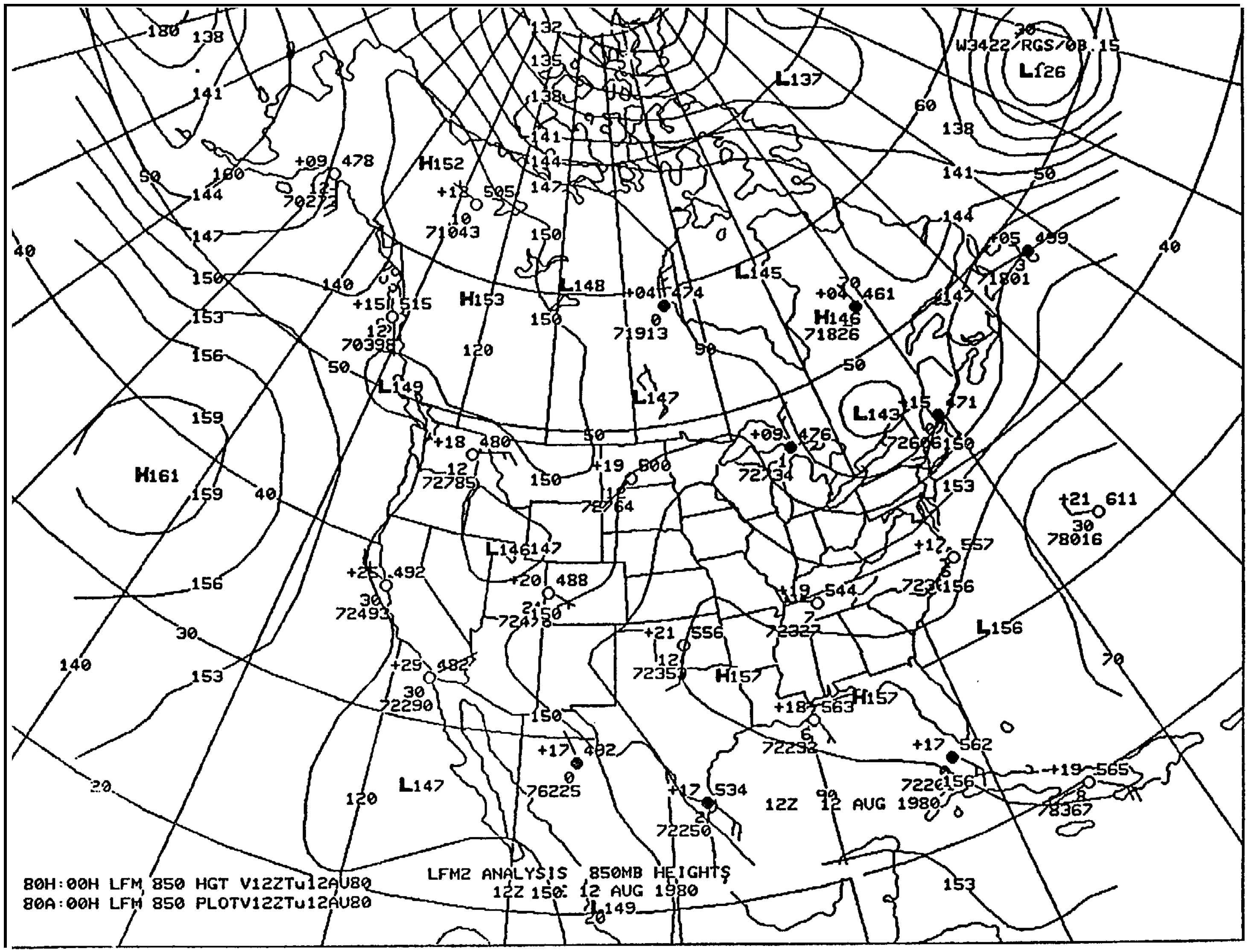


FIGURE 5-2: SAMPLE 850mb PRESSURE SURFACE WITH SOME DATA POINTS SHOWN.

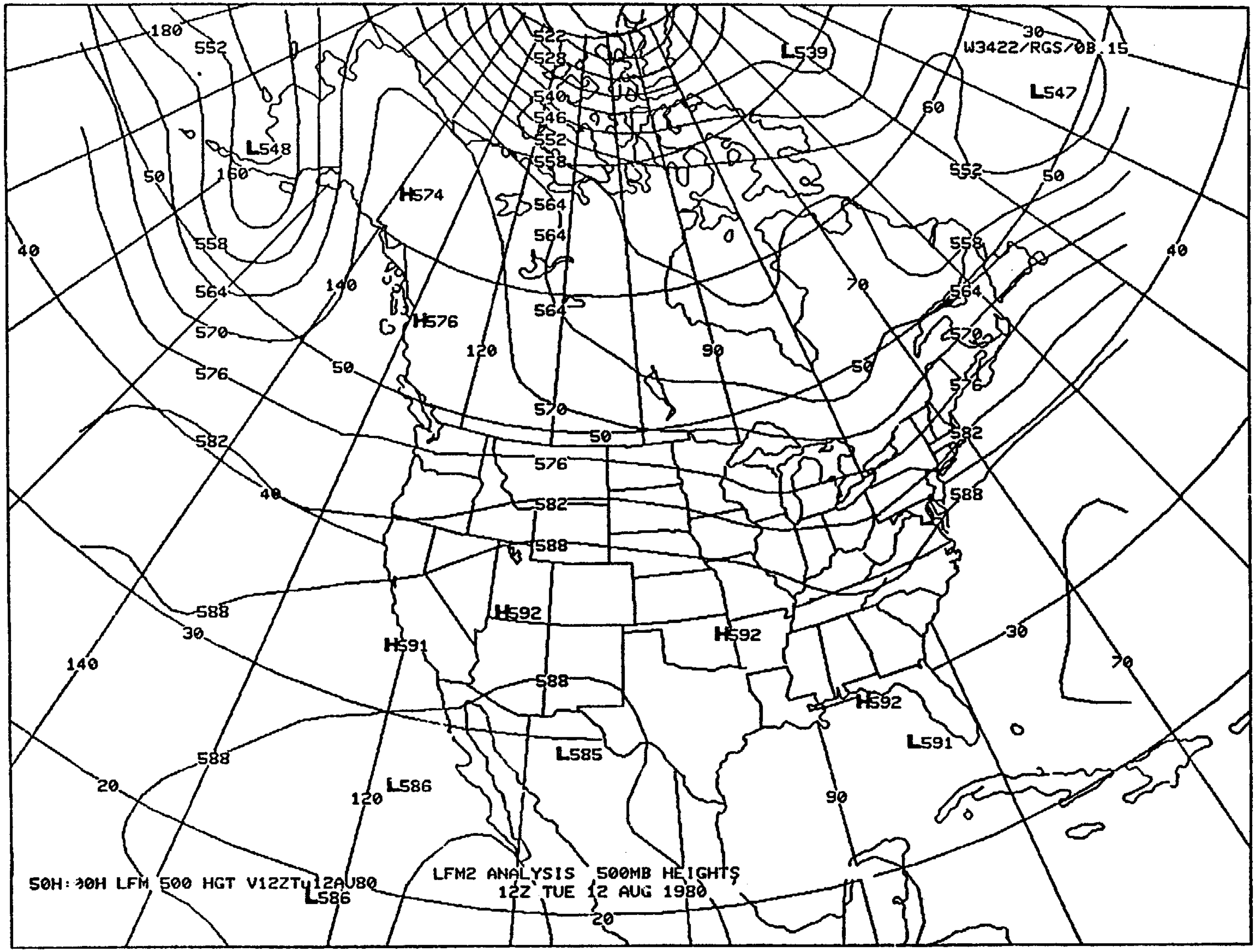


FIGURE 5-3: 500mb PRESSURE SURFACE.

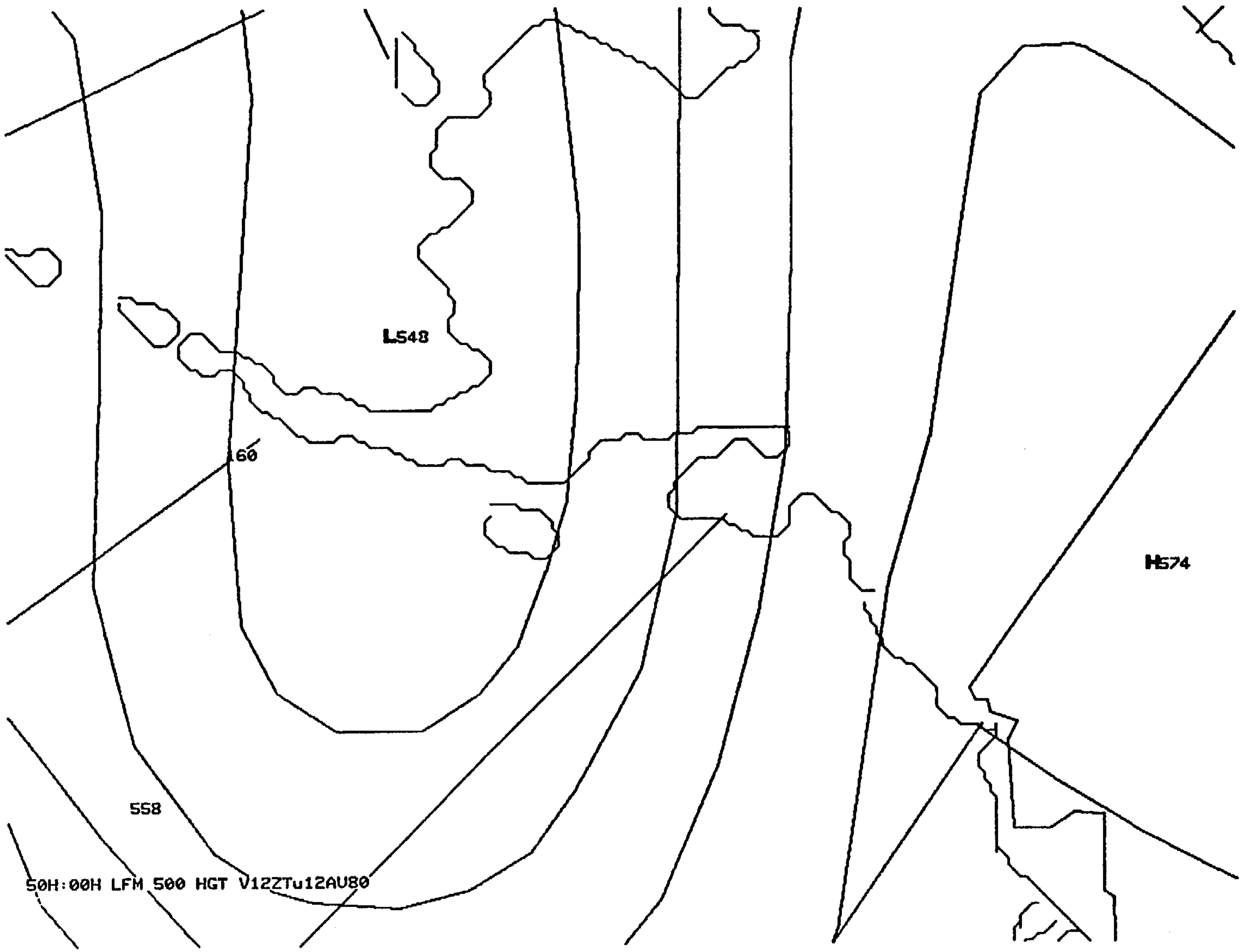


FIGURE 5-4: CLOSEUP OF FIGURE 5-3.

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